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EUROPEAN COOPERATION
ECSS
FOR SPACE STANDARDIZATION

# Space engineering

## Mechanical - Part 5: Propulsion

This ECSS document is a draft standard.
It is therefore subject to change without any notice and may not be referred to as an ECSS Standard until published as such.

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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-E-30 Part 5 Working Group, reviewed by the ECSS Engineering Panel and approved by the ECSS Steering Board.

ECSS-E-30 Part 5B cancels and replaces ECSS-E-30 Part 5.1A which is now part of this Standard.

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# Contents

## Figures



## Tables

# Introduction

This Standard contains normative provisions for:

- solid propulsion for launchers and spacecraft,
- liquid propulsion for launchers,
- liquid propulsion for spacecraft,
- electric propulsion for spacecraft.

Normative provisions that apply to all types of propulsion engineering are given in Clause 4.

A graphical representation of the structure of the document is given in Figure 1

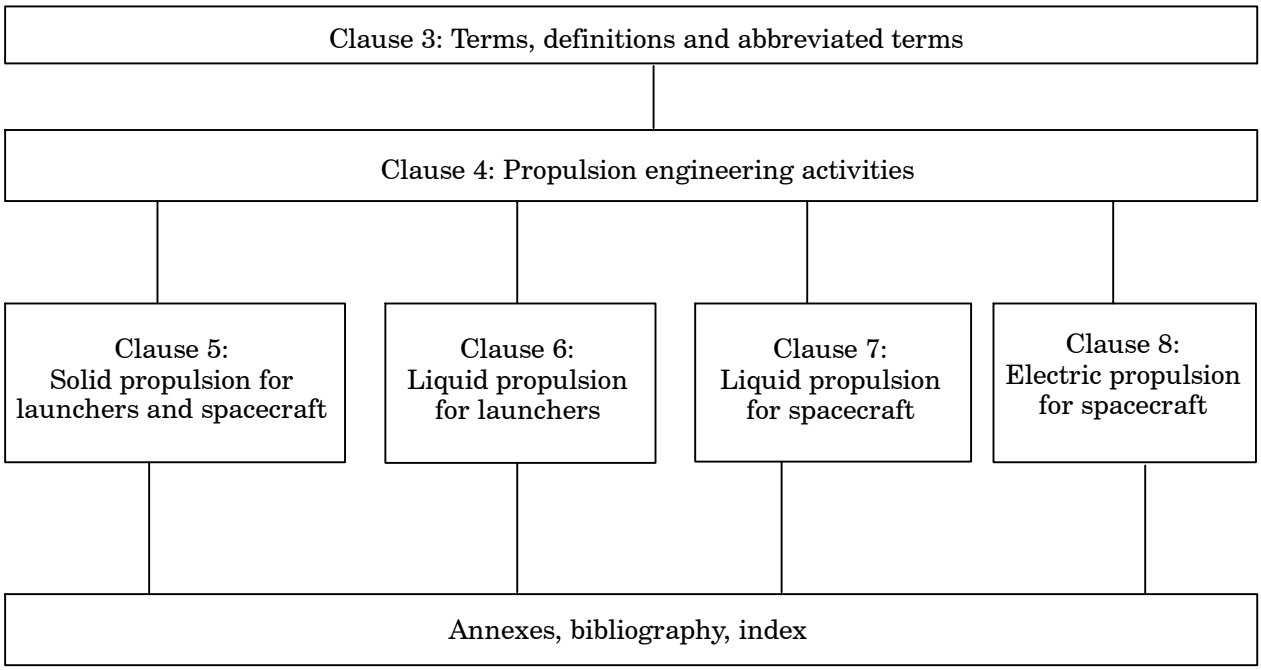


**Figure 1: Structure of this standard**

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# 1

# Scope

All the provisions on propulsions are given in this Part 5 of ECSS-E-30 which forms part of the mechanical discipline, as defined in ECSS-E-00.

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

General requirements for mechanical engineering are defined in ECSS-E-30 Part 1.

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

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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# 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 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-001B | ECSS — Glossary of terms |
| ECSS-E-30 Part 6A | Space engineering — Mechanical — Part 6: Pyrotechnics |
| ECSS-E-30-01A | Space engineering — Fracture control |
| ECSS-Q-70-01A | Space product assurance — Cleanliness and contamination control |
| ECSS-Q-70-02A | Space product assurance — Thermal vacuum outgassing test for the screening of space materials |

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# 3

# Terms, definitions, and abbreviated terms

## 3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in ECSS-P-001 and the following apply.

**3.1.1**
**barbecue mode**
mode where a stage or **spacecraft** slowly rotates in space in order to obtain an even temperature distribution under solar radiation

**3.1.2**
**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 of that thruster exit

**3.1.3**
**buffeting**
fluctuating aerodynamic loads due to vortex shedding

**3.1.4**
**burning time**
$t_b$
time for which the propulsion system delivers an (effective) **thrust**

NOTE Figure 2 illustrates an arbitrary **thrust** or pressure history of a rocket propulsion system. An igniter peak may, but need not, be observed.

Depending on the application, a time, $t_0$, is defined at which the propulsion system is assumed to deliver an (effective) **thrust**, and a time, $t_e$, at which the propulsion system is assumed not to deliver an (effective) **thrust** any more.

The **burning time** is the time interval defined as the difference between the two times: $t_b = t_e - t_0$.

$t_i$ is the time at which the combustion starts and $t_{ign}$ the ignition time.

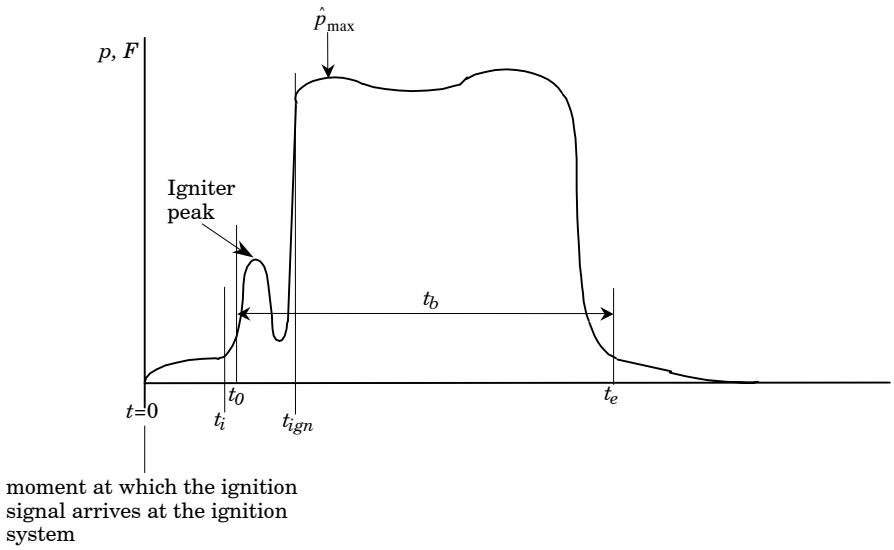



**Figure 2: Burning time**

**3.1.5**
**characteristic velocity**
*C**
<instantaneous characteristic velocity> ratio of the product of the throat area of a rocket engine and the total pressure (at the throat) and the **mass** flow rate

NOTE 1 In accordance with this definition, the instantaneous **characteristic velocity** is:

$$C^* = \frac{P_c A_t}{m}$$

NOTE 2 Instantaneous and overall characteristic velocities are usually referred to as **characteristic velocity**.

NOTE 3 The usual units are m/s.

**3.1.6**
**characteristic velocity**
*C**
<overall characteristic velocity> ratio of the time integral of the product of throat area and total pressure (at the throat) and the **ejected mass** during the same time interval

NOTE 1 In accordance with this definition, the overall **characteristic velocity** is:

$$C^* = \frac{\int_{t_1}^{t_2} P_c A_t \, dt}{\int_{t_1}^{t_2} m \, dt}$$

In many cases $t_1$ is taken to be the ignition time, $t_0$, and $t_2$ is taken to be the time at burnout ($t_e$). In that case, $t_2 - t_1 = t_b$ and the integral in the denominator equals the **ejected mass**.

NOTE 2 Instantaneous and overall characteristic velocities are usually referred to as **characteristic velocity**.

NOTE 3 The usual units are m/s.

**3.1.7**
**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** can be done with dedicated cooling fluids, or with on-board **propellants** that are vented.

**3.1.8**
**component**
smallest individual functional unit considered in a **subsystem**

EXAMPLE Tanks, valves and regulators.

**3.1.9**
**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 the 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 availability of means, and organization policy.

NOTE 4 Adapted from EN 1325-1:1997.

**3.1.10**
**contaminant**
undesired material present in the propulsion system at any time of its life

**3.1.11**
**critical speed**
speed at which the eigenfrequency of the rotor (taking into account gyroscopic effects) coincides with an integer multiple of the rotational speed

**3.1.12**
**cryo-pumping**
condensation of air or nitrogen on $LH_2$ or LHe lines or **components**, thereby sucking in more air or nitrogen and thereby preventing proper **chill-down** of $LH_2$ or LHe lines

**3.1.13**
**de-orbiting**
controlled return to Earth or burn-up in the atmosphere of a **spacecraft** or stage

**3.1.14**
**design**
<result> set of information that defines the characteristics of a product

NOTE Adapted from EN 13701:2001.

**3.1.15**
**design**
<activity> process used to generate the set of information defining the characteristics of a product

NOTE Adapted from EN 13701:2001.

**3.1.16**
**dimensioning**
process by which the dimensions of a **system**, **subsystem** or component are determined and verified, such that the **system**, **subsystem** or component conforms to the **system**, **subsystem** or component requirements and can withstand all loads during its mission

NOTE 1 The reliability requirements can determine the **dimensioning**.

NOTE 2 **Dimensioning** is only possible after the **sizing** process for the particular **system** or **subsystem** has been completed.

**3.1.17**
**discharge coefficient**
$C_d$
inverse of the **characteristic velocity**

NOTE 1 In accordance with this definition, the **discharge coefficient** is $C_d = \frac{1}{C^*}$.

NOTE 2 In this Standard, the units are s/m.

**3.1.18**
**draining**
emptying the fluid contents from a volume

**3.1.19**
**electric thruster**
propulsion device that uses electrical power to generate or increase **thrust**

**3.1.20**
**engine inlet pressure**
**propellant** stagnation pressure at the engine inlet

NOTE Usually, the range for the **engine inlet pressure** is specified. The inlet pressure may be different for oxidizer and fuel.

**3.1.21**
**erosive burning**
increase of the solid burning rate of the **propellant** due to high gas velocities parallel to the burning surface

**3.1.22**
**external**
entity or entities not related to "**internal**" or "**interface**"

NOTE See 3.1.32 for **internal** and 3.1.31 for **interface**.

**3.1.23**
**flushing**
passing a fluid through a volume with the objective of removing any remains of other fluids in this volume

**3.1.24**
**flutter**
aero-elastic instability

**3.1.25**
**graveyard orbit**
orbit about 300 km or more above a GEO or GSO into which spent upper stages or satellites are injected to minimize the creation of debris in GEO or GSO

**3.1.26**
**ground support equipment**
**GSE**
equipment adapted to support verification testing and launch preparation activities on the propulsion **system**

**3.1.27**
**hump effect**
effect by which the solid **propellant** burning rate varies with the penetration depth into the **propellant** grain

**3.1.28**
**hypergolic propellants**
**propellants** which spontaneously ignite upon contact with each other

**3.1.29**
**impulse bit**
time integral of the force delivered by a thruster during a defined time interval

NOTE **Impulse bit** is expressed in Ns.

**3.1.30**
**initiator**
first element in an explosive chain that, upon receipt of the proper mechanical or electrical impulse, produces a deflagrating or detonating action

NOTE 1 The deflagrating or detonating action is transmitted to the following elements in the chain.

NOTE 2 **Initiators** can be mechanically actuated, percussion primers, or electrically actuated (EEDs).

**3.1.31**
**interface**
direct interaction between two or more **systems** or **subsystems**

NOTE It is essential that there is a direct interaction.

**3.1.32**
**internal**
entity or entities of the **system** or **subsystem** itself only

**3.1.33**
**launcher**
vehicle intended to move a separate **spacecraft** from ground to orbit or between orbits

**3.1.34**
**limit testing**
determining experimentally the limit of the maximum expected conditions under which a **system**, **subsystem**, component or material still can be used, or where it demonstrates that it satisfies a specified margin

NOTE The requirement can come from a specification or from the **design** process.

**3.1.35**
**liquid rocket engine**
chemical rocket motor using only liquid **propellants**

NOTE 1 This includes catalytic beds.

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

NOTE 3 The 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 (for non-**hypergolic propellants**);
- valves;
- power systems (pre-combustion chamber and gas generator) if they are present.

**3.1.36**
**maximum expected operating pressure**
**MEOP**
maximum expected pressure experienced by the **system** or **components** during their nominal lifetime

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

NOTE 2 See 4.3.5 for requirements on MEOP.

**3.1.37**
**minimum impulse bit**
smallest impulse delivered by a thruster at a given level of reproducibility, as a result of a given command

NOTE **Minimum impulse bit** is expressed in Ns.

**3.1.38**
**mission**
See **mission life** (3.1.39).

**3.1.39**
**mission life**
life cycle from the delivery to the disposal

NOTE 1 In this standard it is also referred to as **mission**.

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

**3.1.40**
**mixture ratio**
ratio of oxidizer and fuel **mass** flow rates

**3.1.41**
**nozzle**
device to accelerate fluids from a rocket motor to exhaust velocity

**3.1.42**
**net positive suction pressure**
**NPSP**
difference between the static pressure and the vapour pressure at a given temperature

NOTE 1 In accordance with this definition, **NPSP** $= p - p_{vap}(T)$.

NOTE 2 There are 3 types of **NPSPs** (see Figure 3):

- $NPSP_{available}$ which is the **NPSP** at a given instant.
- $NPSP_{cr}$, or critical **NPSP** which is the **NPSP** below which the pump pressure rise decreases dramatically due to cavitation.
- $NPSP_{req}$, or required *NPSP* which is $NPSP_{req} = NPSP_{cr}$ + safety margin.

The safety margin ensures that dynamic loads on the pump, due to asymmetric cavitation are avoided or minimized, and in addition, accounts for uncertainties.

In accordance with these definitions,
$NPSP_{cr} < NPSP_{available}$

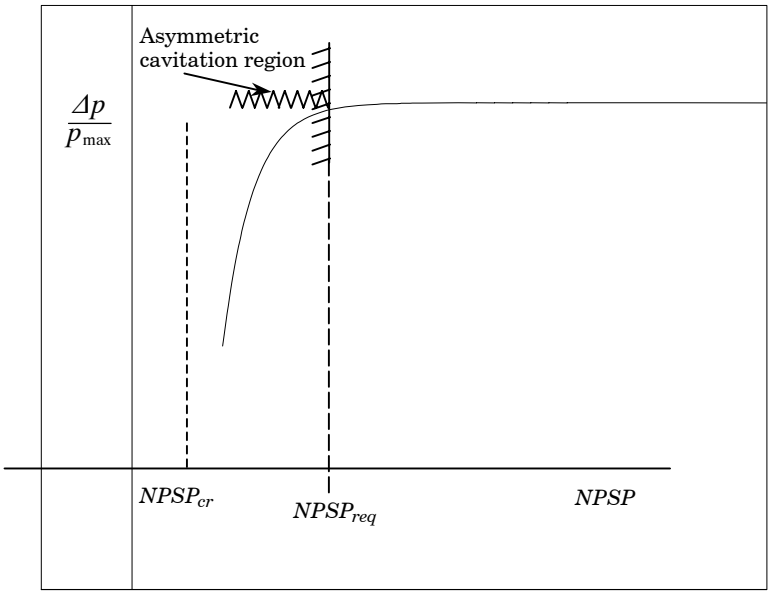



**Figure 3: NPSP**

**3.1.43**
**plasma**
ionized gas

NOTE **Plasma** contains neutral species, ions and electrons.

**3.1.44**
**pre-heating time**
time that the thermal protection is exposed to the hot gases in the “dead water” zone

NOTE The floater (see Figure 4) is assumed to be consumed by the hot combustion products roughly at the same rate as the **propellant** regresses. Between the remaining floater and the thermal protection, a “dead water” zone of hot combustion products exists. Because of the relatively low gas velocity in this “dead water” zone, the heat transfer to the thermal protection is reduced to conduction and radiation only.

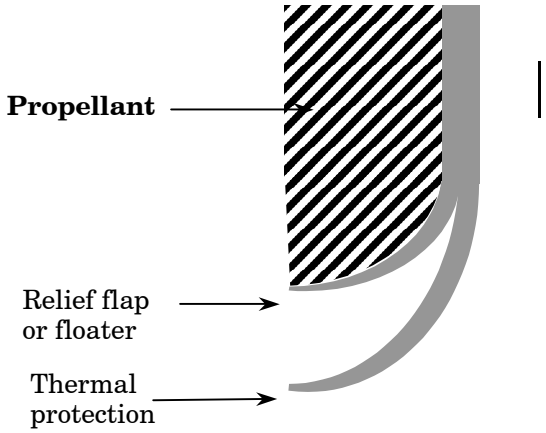



**Figure 4: Relief flap or floater**

**3.1.45**
**pressurant**
fluid used to pressurize a **system** or **subsystem**

**3.1.46**
**pressure drop coefficient (valve)**
coefficient which expresses the pressure drop over a valve

NOTE The pressure drop coefficient is usually represented by $k$, and in accordance with this definition $k=\rho\Delta p/S$.

**3.1.47**
**priming**
ensuring that the **system** or **subsystem** conforms to operational conditions

**3.1.48**
**propellant**
material or materials that constitute a **mass** which, often modified from its original state, is ejected at high speed from a rocket motor to produce **thrust**

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

In chemical rocket motors, either a combustion reaction between two kinds of **propellants** (fuel and oxidizer), or a decomposition reaction (monopropellant), provides the energy to accelerate the mass.

In electric engines 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** (power augmented thrusters, resistojets).

The gas can also be accelerated by a combinations of the above.

**3.1.49**
**propulsion system**
system to provide **thrust** autonomously

NOTE 1 In this standard it is alsdo referred to as the **system**.

NOTE 2 **Propulsion system** comprises all **components** used in the fulfilment of a **mission**, e.g. thrusters, **propellants**, valves, filters, pyrotechnic devices, pressurization **subsystems**,

tanks and electrical **components** such as power sources for electrical propulsion.

**3.1.50**
**purging**
removing gas from a volume containing liquid and gas

NOTE A second meaning of **purging** is **flushing** (see 3.1.23); see also 3.1.79 (**venting**).

**3.1.51**
**pyrogen igniter**
igniter for a (solid) rocket motor producing a heat flux and a flux of hot gases, and that builds up pressure under its own action

NOTE A **pyrogen igniter** resembles a **solid rocket motor**.

**3.1.52**
**pyrotechnic igniter**
igniter for a (solid) rocket motor that primarily produces a heat flux of hot particles but hardly builds up pressure under its own action

**3.1.53**
**repeatability**
ability to repeat an event with the same input commands

**3.1.54**
**re-orbiting**
injection of a **spacecraft** or stage into a **graveyard orbit**

**3.1.55**
**simulant**
fluid replacing an operational fluid for specific test purposes

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

NOTE 2 The **simulant** is selected such that its characteristics closely resemble the characteristics of the operational fluid whose effects are being evaluated in the **system**, **subsystem** or component test.

NOTE 3 The **simulant** is selected such that it conforms to the compatibility requirements of the **system**, **subsystem** or component.

**3.1.56**
**side load**
lateral force on a **nozzle** during transient operation at atmospheric conditions due to asymmetric flow separation

**3.1.57**
**sizing**
process by which the overall dimensions of a **system** or **subsystem** are determined such that the **system** or **subsystem** conforms to the requirements

NOTE At the end of the **sizing** process, functional and material characteristics are also established. The **sizing** process shall conform to the functional requirements.

**3.1.58**
**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 the following:

- a motor case,
- the **internal** thermal protection (**internal** insulation) system,
- the **propellant** grain,
- the **nozzle** or **nozzles**,
- the igniter.

**3.1.59**
**spacecraft**
vehicle purposely delivered by the upper stage of a **launcher** or transfer vehicle

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

**3.1.60**
**specific impulse**
$I_{SP}$
<instantaneous specific impulse> ratio of **thrust** to **mass** flow rate

NOTE 1 The **specific impulse** is expressed in Ns/kg or m/s.

NOTE 2 In engineering, another definition is often 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 $I_{sp}$ (s) is obtained by dividing the $I_{sp}$ expressed in m/s by the standard surface gravity, $g_0$ = 9,806 65 m/s$^2$.

**3.1.61**
**specific impulse**
$I_{SP}$
<average specific impulse> ratio of **total impulse** and total **ejected mass** in the same time interval used for the establishment of the **total impulse**

NOTE 1 See notes for 3.1.60.

**3.1.62**
**subsystem**
set of independent elements combined to achieve a given objective by performing a specific function

NOTE See ECSS-P-001B subclause 3.203.

EXAMPLE Tanks, filters, valves and regulators constitute a **propellant** feed **subsystem** in a **propulsion system**.

**3.1.63**
**system**
See **propulsion system** (see 3.1.49).

**3.1.64**
**termination point**
location, in a bonding application, where the local stress is multi-directional due to a geometric discontinuity

NOTE It can also be referred to as **triple point** (see 3.1.73).

**3.1.65**
**thrust**
generated force due to acceleration and ejection of matter

**3.1.66**
**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**

**3.1.67**
**thrust chamber assembly**
**TCA**
assembly of one or more injectors, igniters, combustion chambers, coolant **systems** and **nozzles**

NOTE There are concepts where one engine has more than one combustion chamber, e.g. a modular plug **nozzle** engine.

**3.1.68**
**thrust coefficient**
$C_F$
<instantaneous thrust coefficient> ratio of (instantaneous) **thrust** and the product of throat area and throat total pressure

NOTE 1 In accordance with this definition, the instantaneous **thrust coefficient** can be calculated as:

$$C_F = \frac{F}{p_c A_t}$$

NOTE 2 Instantaneous and average **thrust coefficients** are usually referred to as **thrust coefficient**.

**3.1.69**
**thrust coefficient**
$C_F$
<average thrust coefficient > ratio of the **thrust** integrated over an appropriate time interval divided by the integral over the same time interval of the product of throat area and throat total pressure

NOTE 1 In accordance with this definition, the average **thrust coefficient** can be calculated as:

$$C_F = \frac{\int_{t_1}^{t_2} F dt}{\int_{t_1}^{t_2} P_c A_t \, dt}$$

In many cases, $t_1$ is taken to be the ignition time, $t_0$,and $t_2$ is taken the time at burnout ($t_e$). In this case, $t_2 - t_1 = t_b$ and the integral of the **thrust** becomes the **total impulse**.

NOTE 2 Instantaneous and average **thrust coefficients** are usually referred to as **thrust coefficient**.

**3.1.70**
**thrust misalignment**
difference between the real and intended direction of the **thrust** vector

**3.1.71**
**thrust out-centring**
**thrust** vector not passing through the instantaneous COM

**3.1.72**
**total impulse**
time integral of the force delivered by a thruster or a **propulsion system** during a given time interval, representative of the operation

NOTE Total impulse is expressed in Ns.

**3.1.73**
**triple point**
See 3.1.64 (**termination point**).

NOTE In this Standard, **triple point** only refers to thermal protection.

**3.1.74**
**turbo pump**
device in a rocket motor consisting of a turbine driven by a high energy fluid, driving one or more rotating pumps in order to deliver specific ranges of fluid **mass** flow rates at specified ranges of pressure

**3.1.75**
**ullage volume**
volume in a tank not occupied by liquid **propellant** and equipment and lines present in the tank

**3.1.76**
**valve load cycle**
loading of the valve according to the extreme envelope, operating the valve or **propulsion system** and returning to ambient conditions

**3.1.77**
**valve manoeuvring time**
moving time of the valve between an initial predetermined position and a final predetermined position

**3.1.78**
**valve response time**
time between the command given to the valve to move and the initial movement of the valve

**3.1.79**
**venting**
opening a closed volume to the ambient with the objective of decreasing the pressure in the volume

## 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 correctly assessing the performance of the propulsion system. The terminology for propulsion related **masses** used in space systems is illustrated in Figure 5.

In Tsjolkowski's equation,

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

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 to the velocity increment according to Tsjolkowski's equation. Examples include: lost oil from TVC systems; **propellant** used to achieve movements around the COM (attitude control). Other **mass** is ejected at lower exhaust velocities, e.g. **mass** used for dump cooling, turbine exhaust gases.

**Mass**

- **Loaded** = **Dry mass**
  + **propellant mass**
  + **pressurant mass**
  + **mass** of (other) fluids
- **Dry** = **Loaded mass** – **propellants** and liquids,
  + igniter **mass** – igniter **propellant**,
  + including gas generator starter mass, – **propellants**,
  + **initiator** masses,
  + including explosive transfer lines
- **End of flight** = **Loaded mass** – **ejected mass**
- **Ejected** = **Propellant mass** (from main combustion chamber at nominal $I_{sp}$)
  + **mass** used for dump cooling (at different $I_{sp}$)
  + **mass** of turbine exhaust gases (at different $I_{sp}$)
  + **propellant mass** used for attitude control
  + jettisoned **mass** consisting of:
    - instantaneously jettisoned mass:
      burst membrane, igniter (consumable)
    - continuously jettisoned mass:
      thermal protection, **nozzle** erosion, grid erosion,
      igniter consumption (ablation or erosion), vented **propellant**,
      TVC lost oil
- **Propellant** = **Mass** of main **propellant**
  + **mass** of igniter and gas generator **propellants** (if ejected)
  + **mass** of **propellant** for attitude control

**Figure 5: Definition of propulsion-related masses**

**3.2.2**
**loaded mass**
**mass** of the propellant system just before activation of the propulsion system

**3.2.3**
**dry mass**
**loaded mass** without consumables, or the initial **mass** without **propellants** and fluids

NOTE 1 **Dry mass** can be weighed.

NOTE 2 It is important to note that explosive transfer lines and pyro valves are usually sealed, so that even when the explosive is consumed, they are not ejected from the **system**.

NOTE 3 Usually, **initiators** are considered to be part of the **dry mass** since the **mass** of the explosive that leaves the propulsion system is negligible; **initiator**s are mounted as "conventional" mechanical equipment.

NOTE 4 For solid propulsion systems, **launchers** or stages, the same definition is used: **dry mass** is the initial **mass** without **propellant mass** (grains and igniter grains).

**3.2.4**
**end of flight mass**
**mass** of the propulsion system directly after the end of the propulsion system operation

NOTE **End of flight mass** = **loaded mass** – **ejected masses**

**3.2.5**
**ejected mass**
sum of the consumed **propellants**, the ejected **pressurant** gases, the instantaneously jettisoned masses and continuously jettisoned masses

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

EXAMPLE An example of consumed **pressurant** gases is the **pressurant** gas sometimes ejected by **spacecraft** operating in blow-down mode.

An example of instantaneously jettisoned masses are the burst membranes and consumable igniters.

An example of continuously jettisoned masses are erosion and ablation products and lost oil from TVC systems.

**3.2.6**
**propellant mass**
sum of the **mass** of the main **propellant**, the gas generator and starter **propellants**, the **propellants** for attitude control, and the igniter **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 |
|---|---|
| **AIV** | assembly, integration and verification |
| **ACS** | attitude control system |
| **AOCS** | attitude and orbit control system |
| **BOL** | beginning-of-life |
| **CFC** | chloro fluoro carbons |
| **CFD** | computational fluid dynamics |
| **COM** | centre of mass |
| **CPIA** | Chemical Propulsion Information Agency |
| **DRD** | document requirements definition |
| **EIDP** | end item data package |
| **EJMA** | Expansion Joints Manufacturer Association |
| **EMC** | electromagnetic compatibility |
| **EMI** | electromagnetic interference |
| **EOL** | end-of-life |

| | |
|---|---|
| **FEEP** | field emission electric propulsion |
| **FMECA** | failure modes, effects and criticality analysis |
| **FOS** | factor of safety |
| **GEO** | geostationary orbit |
| **GSE** | ground support equipment |
| **GSO** | geosynchronous orbit |
| **IATA** | International Air Transport Association |
| **LOx** | liquid oxygen |
| **MDP** | maximum design pressure |
| **MEOP** | maximum expected operating pressure |
| **MLI** | multi layer insulation |
| **MMH** | monomethyl hydrazine |
| **MON** | mixed oxides of nitrogen |
| **MPD** | magneto-plasma-dynamic thruster |
| **NDI** | non-destructive inspection |
| **NPSP** | net positive suction pressure |
| **NTO** | nitrogen tetroxide |
| **OBC** | on-board computer |
| **OBDH** | on-board data handling |
| **ODE** | one-dimensional equilibrium |
| **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 |
| **RFNA** | red fuming nitric acid |
| **STD** | surface tension device |
| **TBI** | through bulkhead initiator |
| **TCA** | thrust chamber assembly |
| **TEG** | turbine exhaust gases |
| **TM/TC** | telemetry/telecommand |
| **TVC** | thrust vector control |
| **UDMH** | unsymmetrical-dimethylhydrazine |
| **VCD** | verification control document |

## 3.4 Symbols

The following symbols are defined and used within this Standard:

| **Symbol** | **Meaning** |
|---|---|
| $\alpha_e$ | half nozzle cone angle (at exit) |
| $\beta$ | thrust deflection angle (for TVC) |
| $C^*$ | characteristic velocity |
| $C_d$ | discharge coefficient |

| | |
|---|---|
| $\mathbf{C_F}$ | thrust coefficient |
| **D** | diameter |
| $\Delta$ | increment |
| **F** | thrust |
| **F** | frequency |
| $\Phi$ | mixture ratio, ratio of oxidizer and fuel mass flow rate. |
| $\mathbf{g_0}$ | standard surface gravity, 9,806 65 m/s$^2$. |
| **h** | enthalpy |
| $\mathbf{I_{sp}}$ | specific impulse |
| **k** | pressure drop coefficient |
| **L** | length |
| **L*** | characteristic length of a combustion chamber |
| $\lambda$ | correction factor for divergence loss |
| **m** | mass flow rate |
| $\mathbf{M_p}$ | total expelled mass |
| $\mathbf{M_0}$ | initial mass of a propulsion system |
| $\mathbf{M_f}$ | mass of the propulsion system at end of motor operation |
| **n-D** | (n is 1,2 or 3) n-dimensional |
| **p** | pressure |
| $\hat{p}_{max}$ | maximum pressure due to ignition |
| $\mathbf{p_{vap}}$ | vapour pressure |
| **S** | surface area or cross section area |
| $\sigma_N$ | normal stress at the interface of a bond |
| **T** | temperature |
| **T** | torque (pumps and turbines) |
| $\mathbf{t_b}$ | burning time |
| $\mathbf{t_i}$ | time at which combustion starts |
| $\mathbf{t_{ign}}$ | ignition time. |
| $\tau$ | shear stress at the interface of a bond |
| $\Delta$**V** | ideal velocity increment of a rocket delivered in a gravitation free environment and without other disturbing forces (drag, solar wind, radiation pressure) |
| $\omega$ | rotational speed |
| $(\ )_{eff}$ | effective |

# 4

# Propulsion engineering activities

## 4.1 Overview

### 4.1.1 Introduction

This Clause 4 (subclauses 4.2 to 4.10) applies to all types of rocket propulsion systems used in space applications, including:

- solid propulsion for launchers and spacecraft;
- liquid propulsion for launchers;
- liquid propulsion for spacecraft;
- electric propulsion for spacecraft.

### 4.1.2 Characteristics of propulsion systems

The specification, design and development of a propulsion system always demands a close collaboration 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 (propellants, simulants and cleaning agents) that can be toxic, corrosive, highly reactive, flammable, dangerous with direct contact (e.g. causing burns, poisoning, health hazards or explosions). The criteria for the choice and use of material 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.a.).
- Risks (e.g. contamination and leakages) are properly analyzed and covered, and RAMS studies are widely performed (see 4.2.b. and 4.2.c.).
- Rocket engines can be subject to instabilities which can result in damage or loss of the motor or the vehicle. Design and development includes the definition of solutions at the system and vehicle level (see 4.2.d.).

### 4.1.3 Relationship with other standards

The requirements defined herein complement the following ECSS engineering standards for specific subjects related to propulsion systems:

- ECSS-E-10 Part 1,
- ECSS-E-20,
- ECSS-E-30 Part 1,
- ECSS-E-30 Part 2,
- ECSS-E-30 Part 3,
- ECSS-E-30 Part 6,
- ECSS-E-30 Part 7,
- ECSS-E-30 Part 8,
- ECSS-E-40,
- ECSS-E-50,
- ECSS-E-70,

NOTE See Clause 2 and Bibliography.

### 4.1.4 Structure of the requirements

The requirements in this Standard are organized as follows:

- There are a set of common requirements applicable to all types of propulsion systems in subclauses 4.2 to 4.10.
- There is a common structure to the requirements, that is compatible with the classification of engineering activities described in ECSS-E-00, as follows:
  - functional;
  - constraints;
  - interfaces;
  - design;
  - GSE;
  - materials;
  - verification;
  - production and manufacturing;
  - in-service (operation and disposal);
  - product assurance;
  - deliverables.

  The requirements in Clause 5 and Clause 8, for each type of propulsion system, are structured thus.

Further information on the use of conventional propellants, pressurants, simulants and cleaning agents is given in Annex A.

## 4.2 General

a. Local regulations for the handling, transportation, and disposal of dangerous or toxic material and fluids shall be strictly applied.

NOTE See ECSS-Q-40.

b. Risks shall be analysed and covered (e.g. contamination and leakages).

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.

e. Standards and procedures additional to those specified in the contracts shall be specified or approved by the customer before use.

## 4.3 Design

### 4.3.1 General

a. Only mature, well tested, validated and well understood designs shall be used.

b. The design should be based on previously qualified designs.

c. Any modification shall be analysed and validated prior to implementation.

NOTE See ECSS-E-10 Part 1.

d. The economical aspects and costs shall be taken into account in the trade-off of different designs.

e. If the system requirements lead to a complex subsystem design, they shall be analysed in order to develop a set of more relaxed requirements that still conform to the higher level requirements.

NOTE 1 Simple solutions are usually selected for reasons of cost and reliability.

NOTE 2 For further details on requirement engineering see ECSS-E-10 Part 1.

### 4.3.2 Global performances

#### 4.3.2.1 Reporting

Global performances shall be analyzed and reported in accordance with:

a. Annex C, for aspect relating to the propulsion performance analysis;

b. Annex K, for aspects relating to the mathematical modelling for propulsion analysis.

#### 4.3.2.2 Overview

For a rocket motor, the most important global propulsion performance parameters are:

- the thrust history,
- the specific impulse history,
- the mass flow rate history,
- the burn time.

The definition of specific impulse is (see 3.1.60):

$$I_{sp} = \frac{F}{m} \quad \text{or} \quad I_{sp} = \frac{\int_{t_0}^{t_e} F dt}{M_p}$$

The total mass flow rate consists of the algebraic sum of all the mass ejected by the engine as follows:

- the main mass flow rate through the nozzle;
- the mass flow rate from dump cooling;
- the mass flow rate from turbine exhaust gases;
- erosion or ablation from the engine internal thermal protection;
- the igniter or starter mass flow rate.

For solid motors, only the (propellant) mass flow rate of the solid propellant grains is taken into account for practical purposes.

For liquid engines, only the (propellant) mass flow rates of the main tanks are taken into account for practical purposes.

The most important derived engine performance parameters are:

- The characteristic velocity, which is a measure of the efficiency of the combustion process in the chamber.
- The thrust coefficient, which is a measure of the efficiency that the nozzle contributes to the thrust.

The engine specific impulse is a measure of the overall engine performance.

The importance of these parameters is that,

- they can be used for comparison of engines, and
- they can be used for comparison between experimental results and theoretical analyses.

For liquid engines, it is important to distinguish the thrust chamber assembly (TCA) performance from the engine performance.

The theoretical values of the derived performance parameters, for every operational point of the engine or TCA, shall be determined.

#### 4.3.2.3 The theoretical specific impulse

The $I_{sp,}$ which can be calculated is subject to losses due to the following:

- injection process,
- combustion,
- flow in the combustion chamber and nozzle,
- boundary layer effects,
- chemical kinetics.

Most of the losses can be estimated by calculation or from experiments. In many cases the specific impulse under vacuum conditions is used.

To estimate the theoretical specific impulse, $I_{sp,}$ global methods may be used: theoretical, empirical or a combination of these.

#### 4.3.2.4 The theoretical characteristic velocity

##### 4.3.2.4.1 Overview

There are, in principle, several methods for assessing the theoretical value for the characteristic velocity, $C^*_{th}$.

$C^*_{th}$ can be calculated by a complete kinetic code that takes into account the chemical kinetics of the reactions. At present, such codes are not generally available.

A simpler approach, that is generally used, is to assume a one dimensional equilibrium (ODE). For this calculation, the following assumptions are made:

- the flow in the combustion chamber is one-dimensional;
- the chemical composition of the products of combustion are in equilibrium with the chemical composition of the environment, which implies that the process is isentropic.

The input parameters for this calculation are as follows:

- The composition and mixture ratio of the propellants.
- The total enthalpy of the propellants (at the outlet of the injector).
- The total pressure in the combustion chamber.

NOTE Because the ODE-type codes assume isentropic conditions, the total pressure in the chamber is assumed to be constant. In reality this is not the case. Therefore, the total pressure to be used as an input is the total pressure at the nozzle inlet, which is the same as the total pressure at the throat.

- The contraction ratio of the chamber at the location where the total pressure has been defined. This value is important for determining the static pressure that affects the chemical composition, especially at lower chamber pressures.
- The number of species to be considered is not limited.

4.3.2.4.2 Theoretical performance calculations

When making theoretical performance calculations the following information shall be available and documented for future reference:

a. The version and type of calculation (code) used.

b. The version and type of the thermodynamic database.

c. Any limitation or reduction in the number of chemical reactions or considered species which has been made for practical reasons.

d. The species considered in the calculations.

EXAMPLE Assessing the effect on the energy balance, if for practical reasons, species have been deleted from the calculations.

NOTE In some cases it is convenient to use the discharge coefficient, $C_d$. The discharge coefficient is the inverse of the characteristic velocity, $C^*$:

$$C_d = \frac{1}{C^*}.$$

4.3.2.4.3 The effective characteristic velocity

a. To obtain the theoretical, effective characteristic velocity, $C^*_{eff}$, the deviations in $C^*$ as discussed in subclauses 6.6.8.4 and 6.6.14.15.2 from the ODE-type and kinetic codes shall be taken into account.

b. The way the deviations in a. are taken into account shall be documented and justified.

c. The justification shall be supported by experimental evidence, where available.

d. The accuracy of the measurements shall be taken into account.

### 4.3.2.5 The theoretical thrust coefficient

4.3.2.5.1 General

a. To determine the theoretical thrust coefficient, $C_{F,th}$, the same code (kinetic or ODE-type) used to determine the theoretical characteristic velocity shall be used.

b. The approximations used to estimate the $C_{F,th}$, shall be documented in detail and justified.

NOTE Usually, the ODE-type codes only give the $C_{F,th}$ for ideal expansion and expansion into a vacuum.

c. Corrections shall be made for non-ideal expansions where exit pressure and ambient pressure are different.

4.3.2.5.2 Kinetic losses

a. The kinetic losses may be estimated by comparing a one dimensional kinetic flow field simulation with the ODE-type simulation.

NOTE Kinetic losses occur due to the difference between the assumed chemical reaction processes in the ODE-type codes and the actual chemical kinetics during the nozzle flow expansion.

b. It shall be ensured that the stagnation conditions in the kinetic code match the stagnation conditions derived from the ODE-type code for the throat (or chamber).

c. It shall be ensured that the different calculations use the same chemical species.

#### 4.3.2.5.3 Fluid dynamic losses

It shall be ensured that the same chemistry model is used as in the ODE-type simulation.

NOTE Fluid dynamic losses are caused by the non-axial flow in the exit section of the nozzle.

For conical nozzles, the loss is derived from Malina's correction factor, λ:

$$\lambda = \frac{1 + \cos\alpha_e}{2},$$

where:

$\alpha_e$ is the nozzle half cone angle; the actual loss is 1 – λ.

For bell nozzles, the losses may be established from an axi-symmetric two-dimensional flow field simulation.

#### 4.3.2.5.4 Boundary layer losses

Boundary layer losses are due to viscous flow effects close to the wall. The losses depend on the gas transport properties, the wall surface roughness and the wall temperature. Note that the roughness can change with (repeated) use of the nozzle. The wall can, by catalytic effects affect the composition of the boundary layer. For composite material nozzles, there can also be a chemical reaction between the nozzle flow and the wall material.

The boundary layer losses can be estimated by comparing a two dimensional viscous flow field simulation with a two dimensional in viscid flow field simulation using the same chemistry.

A simpler approach is to solve the boundary layer equations and determine the momentum loss thickness. This method usually leads to a good estimate of the boundary layer loss.

The boundary layer also affects the heat transfer from the core flow to the nozzle wall.

#### 4.3.2.5.5 The effective thrust coefficient

a. To determine the effective thrust coefficient, $C_{F,eff}$, the loss for each case, $i$, should be determined in $\Delta C_{Fi}$, $\Delta C_{Fi} = \frac{Loss_i}{P_c A_t}$.

b. If a. is not carried out, justification shall be provided.

c. The effective thrust coefficient, $C_{F,eff}$ shall be calculated as follows:

$$C_{F,eff} = C_{F,th} - \sum_{i}^{N} \Delta C_{Fi}.$$

d. The thrust efficiency, $\eta_{C,F}$, defined as: $\eta_{C,F} = \frac{C_{F,eff}}{C_{F,th}}$, shall be determined.

#### 4.3.2.6 The effective specific impulse

The effective specific impulse, $I_{sp,eff}$, is the theoretical specific impulse, $I_{sp,th}$, corrected for all the losses and gains ($I_{sp,eff} = I_{sp,th} - \Delta\Sigma I_{sp}$). According to the definitions of $C^*_{eff}$ and $C_{F,eff}$, the effective specific impulse, $I_{sp,eff}$, may be determined from:

$$I_{sp,eff} = C^*_{eff}\, C_{F,eff}.$$

#### 4.3.2.7 Efficiencies

##### 4.3.2.7.1 Overview

The efficiencies of the characteristic velocity, $C^*$, thrust coefficient, $C_F$, and specific impulse, $I_{sp}$, are obtained by taking the ratio of the experimental and effective values:

$$\eta_{C^*} = \frac{C^*_{\exp}}{C^*_{eff}}$$

$$\eta_{C,F} = \frac{C_{F,\exp}}{C_{F,eff}}$$

$$\eta_{I,sp} = \frac{I_{sp,\exp}}{I_{sp,eff}}$$

##### 4.3.2.7.2 Normative provisions

The designer shall

a. take the values of $I_{sp}$, $C^*$ and $C_F$ into account at an early stage (project Phase A and B),

b. apply corrections to the theoretical values to obtain realistic estimates, and

c. provide justification for the estimates.

NOTE For project phases, see ECSS-M-30.

### 4.3.3 Aerodynamic effects

#### 4.3.3.1 Overview

During atmospheric flight there is an interaction between the external flow around the launcher and the nozzle exhaust flows. These flows mix, while the mixing process itself is governed by the velocity and density ratios of the external flow and the nozzle flows.

For many launcher or stage configurations this results in a non-steady re-circulating flow pattern in the launcher base area.

This non-steady re-circulating flow can introduce severe, non-steady, asymmetric side loads on the nozzles and heating of the launcher base area.

#### 4.3.3.2 Normative provisions

a. The side loads (buffeting) introduced by non steady re-circulating flow shall be estimated and taken into account in:

   1. the nozzle design (structural), and

   2. the design of the TVC actuators.

b. As the estimate of these side loads can be very inaccurate, large margins of uncertainty should be agreed with the customer and applied.

c. As the non-steady side loads (buffeting) can also affect other propulsion components in the base area of the launcher or the stage, these loads shall be taken into account in the structural design of these components.

d. The changing loads on the nozzle extension that result from the decreasing ambient pressure as the (aerodynamic) velocity increases, shall be analysed and taken into account the design of the nozzle extension.

e. As aerodynamic heating can become important at high launcher velocity, the following shall be done:

1. Thermal analysis
   (a) analize the aerodynamic heating effects and take them into account in the thermal analysis of the propulsion system;
   (b) report the thermal analysis, as specified in (a), in accordance with Annex E.
2. Thermal protection:
   The thermal protection shall be analysed and taken into account in the design of the thermal protection.

f. For the steady state aerodynamic loads on propulsion system components that are exposed,, exterior aerodynamics shall be determined and taken into account in the design of these components.

g. The acoustic frequencies and amplitudes of the acoustic noise, during the flight of a launcher, caused by the following, shall be estimated or determined:

1. The various operating propulsion systems on the launcher (e.g. boosters, main stage engines).
2. The non-steady aerodynamics.

h. It shall be ensured that the acoustic noise specified in g. does not jeopardize the following:

1. the pressurization system (liquid propulsion systems),
2. the propellant feed system (liquid propulsion systems),
3. the structural integrity of the propulsion system.

i. The effects of the interactions between the first stage or booster propulsion systems of the launcher and the launch pad on the launcher propulsion systems shall be analysed and taken into account in the design of all the propulsion systems.

j. The analysis specified in i. shall be reported in accordance with Annex G.

k. The effects specified in i. shall include the following:

1. shock waves (pressure),
2. heating,
3. vibrations.

### 4.3.4 Reference envelopes

#### 4.3.4.1 Operational envelope

##### 4.3.4.1.1 Overview

The set of nominal data in which the propulsion system, subsystem, or component should operate is called the operational envelope.

##### 4.3.4.1.2 Normative provisions

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

b. The propulsion system or subsystem shall be capable to function within the operational envelope specified in a.

NOTE During the design process, the launcher, spacecraft or stage requirements usually change; it is therefore prudent to take this into account when defining the operational envelope.

c. The operational envelope shall be based on the following parameters:

1. The range of parameters during flight and testing.

   NOTE For liquid engines this includes, for example, changes in inlet pressure and inlet temperatures during flight and, if specified, re-ignition.

2. Deviations in the propellant or engine tuning.

   NOTE For solid motors this includes variations in the rate of burning.

3. Deviations in the various modelling processes.
4. Deviations in component performances.
5. Deviations in manufacturing.
6. Deviations in measurements.

d. Addition of independent deviations shall be made statistically.

e. The same deviations shall not be taken into account more than once.

f. The operational envelope shall

1. be used for the initial design of propulsion systems, subsystems and components, and
2. encompass the envisaged mean flight conditions.

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

#### 4.3.4.2 Qualification envelope (test)

a. The engine and its systems, subsystems and components shall be qualified to ensure that the engine, system, subsystems and components function properly in the whole operational envelope, including scatter and deviations.

   NOTE This means that the qualification envelope is larger than the operational envelope.

b. The boundaries of the qualification envelope shall be determined using statistical methods.

c. When defining the qualification envelope, the following shall be taken into account:

1. deviations in the propellant or engine tuning;
2. deviations in the modelling processes;
3. deviations in the component performances;
4. deviations in manufacturing;
5. deviations in measurements.

#### 4.3.4.3 Extreme envelope (margins)

a. As the qualification envelope is larger than the operational envelope, the propulsion system, subsystem or component design shall be such that the propulsion system, subsystem or component is able to successfully pass the qualification tests.

b. As the boundaries of the qualification envelope include statistical uncertainties, the extreme statistical uncertainties, which exceed the qualification envelope, shall be added to the qualification envelope in order to define the extreme envelope.

c. The propulsion system and subsystem design shall take the extreme envelope into account.

d. To define the extreme envelope, the following shall be taken into account:

1. deviations in the component performances;
2. deviations in the manufacturing;
3. deviations in the measurements.

e. The design shall be based on the extreme envelope.

NOTE The extreme envelope strongly affects the reliability assessment.

### 4.3.5 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. FOS × MEOP ≤ MDP.

NOTE 1 The maximum expected operating pressure, MEOP, for a system, subsystem or component is derived from the extreme envelope.

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

### 4.3.6 Sizing

#### 4.3.6.1 General

a. The sizing process shall start by taking the results of the propulsion system selection into account.

b. The sizing process shall start by considering the system requirements.

c. The functional requirements, operating and special constraints, loads, interfaces and mission requirements shall be taken into account.

d. Subsequently, all functions during the mission shall be identified.

e. The sizing process shall also consider industrial, transport, environmental constraints and imposed and forbidden solutions or technologies.

f. The sizing process shall take the results of the FMECA and safety requirements into account.

NOTE For FMECA, see ECSS-Q-30-02.

g. The sizing process shall take the margins based on reliability and safety into account.

#### 4.3.6.2 Sizing cases

##### 4.3.6.2.1 General

a. The results of the application of the requirements specified in 4.3.6.1 shall be taken into account for the sizing of the propulsion system, its subsystems and components.

b. Dimensioning cases and criteria shall be established for the system and every subsystem and component.

c. The dimensioning criteria shall take into account the performance and functional requirements.

##### 4.3.6.2.2 Ageing: overview

Some materials (e.g. solid propellants, energetic materials, polymers, composite materials, glues, putty, grease) are susceptible to ageing, that is, their characteristics change by natural processes with time.

The degree of change depends on the materials, the form of the materials and their assembly, storage and mission conditions (e.g. loads, temperatures, humidity, time).

##### 4.3.6.2.3 Impact of ageing on sizing and dimensioning

For sizing and dimensioning the effect of ageing described in 4.3.6.2.2 shall be taken into account, with respect to the expected duration of, and the conditions during, the mission (e.g. radiation, atomic oxygen, humidity and thermal environment).

##### 4.3.6.2.4 Dimensioning

a. The dimensioning cases shall include a list of load combinations that are critical.

b. The load combinations specified in a. shall be:

   1. Determined from the identified mechanical and thermal loads, pressures, temperatures, and temperature gradients based on the functions to be performed by the system, subsystem or component during the mission.

      NOTE See ECSS-E-30 Part 1, Part 2, Part 6, Part7, and Part 8.

   2. Reported in accordance with Annex E.

c. If during manufacturing, handling testing and transport, the loads on structural elements, components, subsystems or systems exceed the loads for which they have been dimensioned, the conditions for manufacturing, handling, testing and transport should be modified such that the loads conform to the dimensioning loads.

d. If c. is not met, the loads specified shall be taken into account in the design.

e. If an analytical approach cannot be applied to obtain sizing or dimensioning, state of the art rules and experience shall be used.

f. In areas where there is a lack of understanding of the underlying physical and chemical processes, the solution shall be well justified and documented using state of the art rules and experience.

g. Areas where there is a lack of understanding of the underlying physical and chemical processes and where there is no experience shall only be applied after a thorough development program able to give confidence in the proposed solution.

h. During the sizing and dimensioning process, the data that are used in the calculations shall be documented, and include a description of the calculation methods used, their limitations and restrictions.

i. The sizing and dimensioning process shall take into account the identified failure modes.

j. Catastrophic failure modes shall be specifically analysed.

### 4.3.7 Imbalance

#### 4.3.7.1 General

Several types of imbalance can occur, either at engine level or at propulsion system level (e.g. mass imbalance, pressure imbalance, angular momentum imbalance, thrust imbalance).

#### 4.3.7.2 Angular momentum imbalance

##### 4.3.7.2.1 Overview

Angular momentum imbalance is caused by the (different) angular momentums of the fuel and oxidizer (turbo) pumps.

Other potential causes for perturbing torques or perturbing angular momentums are:

- the nozzle boundary layer (see subclause 6.6.9.6.3),
- swirl in the propellant tanks,
- swirl in the turbine exhaust gas,
- TVC,
- thrust misalignment,
- jet damping, and
- changes in the inertial properties of the system.

4.3.7.2.2 Normative provisions

a. The effects of angular momentum (perturbations) shall be quantified during the development and taken into account in the design of the propulsion control system.

b. The angular momentum imbalance shall conform to the system requirements.

#### 4.3.7.3 Thrust imbalance

4.3.7.3.1 Overview

If the thrust is delivered by multiple engines, there can be an imbalance as a result of differences in thrust between the various engines.

In all cases, thrust imbalance causes the resulting thrust vector not to pass through the (instantaneous) COM.

4.3.7.3.2 Normative provisions

a. The effects of thrust imbalance shall be taken into account in the design of the control system.

b. The thrust imbalance shall conform to the system requirements.

#### 4.3.7.4 Thrust misalignment and thrust out-centring

a. The effects of thrust misalignment and thrust out-centring shall be taken into account in the design of the propulsion system and the design of the control system.

b. The thrust misalignment and thrust out-centring shall conform to the system requirements.

c. The derived results shall be justified.

### 4.3.8 Thrust vector control

#### 4.3.8.1 Overview

Thrust vector control (TVC) can be used to adjust the direction of the thrust vector on command.

Presently the TVC system generally used for solid motors employs nozzles with a flexible bearing. For liquid engines, a combustion chamber or engine with a gimbal joint or ball joint, dedicated control engines, or separate small combustion chambers and nozzles integrated with the main engine are used.

TVC may also be accomplished by alternative methods, for example:

- fluid injection,
- partial blockage of the flow,
- vanes.

These are not within the scope of this Standard.

#### 4.3.8.2 Nozzle deflection

##### 4.3.8.2.1 Actuation methods

For nozzle deflection or gimbaling, the following actuation methods are used:

- Blow-down system, where oil is pressurized by a high-pressure gas. The actuator is activated by the oil that is ejected from the actuator (see 4.3.8.2.2). The TVC capacity, amongst others, is determined by the amount of oil stored.
- Pumped oil system, where the oil is pressurized by a pump. The low pressure oil returning from the actuator is again pressurized by the pump. The pump is either powered by a high-pressure (hot) gas or by an electric motor.
- A direct mechanical actuation using an electric motor.
- Electro-hydrostatic actuator, that is a closed system where there are no valves and the direction of the oil flow is determined by the sense of rotation of an electrically driven pump.

##### 4.3.8.2.2 Blow-down systems

For the blow-down systems described in 4.3.8.2.1:

a. It shall be ensured that the oil is ejected in such way that its combustion does not endanger the system or subsystem.

b. The oil should be ejected close to the nozzle exit.

#### 4.3.8.3 Parameters at system and subsystem level

a. The following parameters shall be available from the system requirements:

1. Static accuracy, $\beta_{\max}$, $\left(\dot{\beta}\right)_{\max}$, $\int_{t_1}^{t_2} \left|\dot{\beta}\right| d\tau$

   where $\beta$ is the thrust deflection angle and $t_1$ and $t_2$ define the time interval over which the motor or engine is specified to provide TVC).

2. The bandwidth of the TVC-actuation system in terms of frequency and phase lag.

b. Starting from this data, conformance to the system and subsystem requirements shall be established and verified.

c. It shall be verified that the system is not be subject to unstable dynamic behaviour.

NOTE The maximum gimbal acceleration, $\left(\ddot{\beta}\right)_{\max}$ is an important output parameter for the mechanical design of the motor or engine.

#### 4.3.8.4 Parameters at motor or engine level

At the motor or engine level, the following parameters shall be known:

a. Mass, inertia and COM of the movable part of the nozzle or engine.

b. The torque including all parameters contributing to it:

- aerodynamic moments;
- for solid motors, the resistance of the thermal protection of the flexible joint and resistance of the flexible joint;
- for liquid engines, the pressurization of propellant feed lines;
- the spring-back and friction of the feed-line flexible joints;
- the resistance of the gimbal joint or ball joint.

c. For solid motors, the position of the centre of rotation of the flexible nozzle.

d. For liquid engines, the position of the centre of rotation of the engine or combustion chamber.

e. For solid motors, the displacement of the centre of rotation of the flexible nozzle under pressure.

f. The attachment points of the actuators.

g. The stiffness of the attachment points, stage structure and engine structure.

h. For solid motors the stiffness (radial and axial) of the flexible seal.

i. For liquid engines, if the whole engine is gimbaled, the gyroscopic moment of the turbo pump.

#### 4.3.8.5 TVC and structure deformation interaction

a. The coupling between the TVC-deflection and the deformation of the structure shall be analysed and accounted for.

b. It shall be ensured that no resonance between the TVC-action and the structural deflection occurs.

#### 4.3.8.6 Forces and loads

a. For TVC-systems (for sea-level launched engines), the forces due to side-loads on the nozzle shall be taken into account.

b. The effect of thrust misalignment on the TVC and the resulting forces on the actuators and the power supply system shall be taken into account.

c. For the TVC system the following shall be done:

   1. Verify that the TVC system can withstand all the thermal and mechanical loads (internal and external) and retains its integrity during the mission.

   2. Report the thermal analysis specified in 1. in accordance with Annex E.

d. The mechanical loads during the transient phases shall be analysed and include the following:

   1. ignition (side-loads),

   2. shutdown and burn-out (side-loads, only during ground tests),

   3. lift-off,

   4. stage-separation,

   5. the loads due to buffeting.

e. The analysis specified in d. shall be reported in accordance with Annex I.

#### 4.3.8.7 Roll control

a. Roll control of a stage or spacecraft may be accomplished by:

   1. the main propulsion system if it has two or more (movable) nozzles;

   2. dedicated control engines.

b. If no dedicated control engines or nozzles are used, the impact of the integrated roll control system on the main propulsion system shall be carefully analysed.

c. It shall be ensured that the interaction of the integrated control system with the main propulsion system does not adversely affect the operation of the main propulsion system.

## 4.4 Pyrotechnic devices

Interfaces for mounting pyrotechnic devices on the system, subsystem, motor or engine shall be defined at motor or engine level.

NOTE 1 For pyrotechnic devices, see ECSS-E-30 Part 6.

NOTE 2 For solid propulsion systems, mounting of pyrotechnic devices is covered in the requirements of 5.6.5.3.4 and 5.6.5.5.

## 4.5 Materials

Propellant, pressurant, simulant, or cleaning agents shall be

a. selected according to 4.2.e. if standards are available, and

b. used in conformance with such standards.

NOTE 1 Standards on the use of conventional liquid propellants, pressurants, simulants and cleaning agents are given in Annex A.

NOTE 2 For selection of material, see ECSS-Q-70 and ECSS-E-30 Part 8.

## 4.6 Verification

### 4.6.1 General

#### 4.6.1.1 Envelopes

a. The verification shall be performed in conformance to a standard conforming to 4.2.e.

NOTE For verification, see ECSS-E-10-02.

b. For every system, subsystem or component, the envelopes (see 4.3.3) shall be defined.

c. Every system, subsystem, or component shall conform to the requirements of the extreme envelope (see 4.3.4.3).

NOTE The extreme envelope defines the design requirements.

d. It shall be verified that the extreme envelope for every system, subsystem and component conforms to the system, subsystem and component requirements.

e. The verification specified in a. to d. shall be documented.

#### 4.6.1.2 Verification plan

a. A verification plan shall be established in the development and ground qualification phase.

b. The verification plan specified in a. shall include the following:

1. Definition of:

(c) how to execute the verification;

(d) the activities to be performed for the verification.

2. Identification of the requirements or phenomena resulting from the extreme envelope that cannot be verified or reproduced during the ground development phase.

NOTE Examples of requirements that cannot be verified during the development and ground qualification phase are: behaviour of propellants in low “g” conditions, ignition and performance of large engines in vacuum, POGO for upper stages, the effect of buffeting on the propulsion system, the effect of asymmetric heat fluxes on boosters and the effect of a long period in space.

c. For the requirements or phenomena that are identified in b.2., the justification shall be documented.

d. Requirements or phenomena that cannot be verified or reproduced during the development and ground qualification phase should be verified during the qualification flight.

#### 4.6.1.3 Data collection

a. The propulsion system shall have functionality to enable the measurement of data, in conformance to the requirements.

b. An analysis plan shall be established, specifying the analyses to be made, the extent of the analyses, and identifying the software to be used and be developed.

c. The test conditions shall be established, specifying the data to be measured.

NOTE See ECSS-E-10-02A, subclause G.8.10.

d. The test conditions shall be in accordance with the specific measurement objectives, e.g. development test, qualification test, flight measurements.

NOTE See ECSS-E-10-02A, subclause G.8.10.

e. The test conditions shall be in accordance with the measurement objectives for:

1. verification of the behaviour of the propulsion system, subsystem and component;
2. validation of models;
3. environmental loads, e.g. acoustics, heat fluxes and vibrations.

NOTE See ECSS-E-10-02A, subclause G.8.10.

#### 4.6.1.4 Verification of requirements

Verification of conformance to the requirements shall comprise the following steps:

a. Establish a verification plan consisting of

1. an analysis plan, and
2. the test conditions.

NOTE See ECSS-E-10-02A, subclause G.8.10.

b. Define the product (system, subsystem, component).

c. Verify that the product definitions conform to the requirements of the extreme envelope (design envelope, see 4.3.4.3).

d. Qualify the product, i.e. demonstrate that the product conforms to all the requirements for the qualification envelope (see 4.3.4.2).

e. Perform reception tests, i.e. verify that the product conforms to the specific verifiable requirements (e.g. proof tests), specified in:

1. Table 3 for solid propulsion,
2. Table 11 for liquid propulsion.

#### 4.6.1.5 Verification approach

a. Verification can be performed by analyses, tests or a combination of these.

b. A verification control document, VCD, shall be established.

NOTE For the VCD, see ECSS-E-10-02

c. A compliance matrix shall identify the requirements that are verified by analysis, by test, or by both.

### 4.6.2 Verification by analysis

a. Verification by analysis shall be performed according to the analysis plan.

NOTE In this Standard, "verification by analysis", includes, "verification by review of design" and "re-flight" verification.

b. The analyses, according to the compliance matrix, shall demonstrate that the system, subsystem or component function properly during the operation of the system, subsystem or component as defined by the extreme envelope under:

1. mechanical loads and
2. thermal loads.

NOTE This contributes to the reliability assessment.

c. The analyses, according to the compliance matrix, shall demonstrate that the propulsion system conforms to the corresponding mission requirements.

d. An agreement between all parties shall be reached on the

1. the calculation methods,
2. the software, and
3. the databases

to be used

NOTE Such an agreement needs no exchanging 'confidential information'. It serves to inform all participating parties and avoid confusion when the results of the analyses are being reviewed.

e. The verification by analysis shall specifically address the following:

1. Motor performance (e.g. thrust, pressure, burn time, total impulse), steady state and transient.
2. COM, shift of the COM and changes in inertial properties.
3. Characteristics of the nozzle flow and the nozzle exhaust.
4. For liquids, the effect of sloshing.
5. The interfaces.
6. Subsystem dimensioning (thermal, mechanical).
7. The margins for the failure modes identified by the FMECA.

NOTE For FMECA, see ECSS-Q-30-02.

8. The safety aspects (e.g. effects of explosion and fire) during manufacturing, transport, handling, storage, ground operation and launch.

f. For the verification by analysis the following shall be reported:

1. The transient analysis specified in e.1. in accordance with Annex I.
2. The analysis specified in e.3. shall be in accordance with Annex G.
3. The analysis specified in e.4. shall be in accordance with Annex H.

g. Validated analysis methods should be used.

h. If f. is not satisfied, the analysis methods used shall be validated during the development phase.

i. Thermal analysis shall be reported in accordance with Annex E.

j. Mathematical modelling shall be reported in accordance with Annex K.

### 4.6.3 Verification by test

#### 4.6.3.1 General

a. A plan for the test configurations, the test instrumentation, and the test stand shall be established taking into account the limited number of tests.

NOTE 1 For verification by test, see ECSS-E-10-02.

NOTE 2 The firing test configuration (horizontal or vertical) can affect the test results especially for solid motors while it also affects the design.

b. Measurements shall be taken in conformance to the subsystem or system requirements, at critical or specific locations, to obtain parameters which include:

1. shocks, vibrations (in at least two orthogonal directions: axial and radial);
2. displacements and deformations;
3. temperatures;
4. thermal fluxes in the nozzle area;
5. external acoustic pressures and frequencies (for first stage and booster engines only);
6. external pressure;
7. for solid motors, the grain temperature.

NOTE Other measurements can be made (e.g. optical and ultrasonic measurements).

c. Measurements shall not:

1. endanger personnel,
2. endanger equipment,
3. invalidate measurements of other parameters.

d. The conditions during ground testing should reproduce the expected flight conditions.

e. Any differences between the ground test conditions and the expected flight conditions shall be identified and documented.

f. The effects of these differences on the operation and reliability of the propulsion system should be analysed.

g. Special hardware, not fully representative of the flight hardware, but which has the functionality of the hardware, may be used during development tests (e.g. “battleship” hardware).

h. The verification by test, to determine whether a system, subsystem or component conforms to the requirements, according to the compliance matrix, shall proceed in three steps:

1. Development tests

NOTE The requirements for the development test are given in the following subclauses:

- For solid propulsion systems for spacecraft and launchers, subclause 5.8.3.
- For liquid propulsion systems for launchers, subclause 6.8.3.
- For liquid propulsion for spacecraft, subclause 5.6.3 of ECSS-E-30 Part 5.1.
- For electric propulsion for spacecraft, subclause 6.7.3 of ECSS-E-30 Part 5.1.

2. Ground qualification tests

NOTE During the ground qualification tests, the system, subsystem, or component is tested within the qualification envelope. The objectives are as follows:

- To demonstrate that the manufacturing processes and procedures result in a product that conforms to the qualification requirements.
- To demonstrate that the system, subsystem, or component function properly using the manufacturing processes and procedures.
- To define the acceptance tests and criteria for flight hardware.

The successful completion of the ground qualification tests, together with the analyses, provides the in-flight prediction model.

3. Qualification during flight

NOTE Flight measurements are limited by telemetry performance and cost. Usually, pressure, acceleration, nozzle deflection (in the case of TVC) and some temperatures are measured.

During flight qualification, conformance of the system, subsystem, or component to the specified flight performance and analysis predictions shall be verified, based on the ground qualification tests.

During flight qualification, it is verified conformance of the interaction between the launcher or spacecraft and the propulsion system to the launcher or spacecraft qualification envelope shall be verified.

i. During the qualification:

1. only qualifiable industrial processes shall be used to manufacture, control and test systems, subsystems, and components;
2. the ground qualification item shall be identical to the flight qualification item;
3. the flight qualification item shall be identical to the production items, including manufacturing and control processes.

j. Thermal analysis shall be reported in accordance with Annex E.

#### 4.6.3.2 Tests on systems, subsystems and components

##### 4.6.3.2.1 Overview

There are two types of verification by test:

- A verification that the materials, components, subsystems or systems conform to the requirements and specifications derived from the operating and system requirements. This test includes, for example, incoming inspection, proof tests, integration tests, lot acceptance tests (acceptance).
- A verification that the materials, component, subsystem or system conform to the qualification requirements (see 4.3.4.2) and to the qualification envelope. This test includes, for example, burst tests and test firing of the motor.

NOTE The verification of qualification envelope requirements, and acceptance tests for materials, components, subsystems and systems, are listed in the following subclauses:

- For solid propulsion systems for spacecraft and launchers, in 5.8.3.3.
- For liquid propulsion systems for launchers, in 6.8.3.4.

#### 4.6.3.2.2 Proof pressure or proof spinning test

a. Proof pressure and proof spinning tests shall be performed depending on the performed NDI, load assumptions used for design and applied safety rules on all pressure vessels and pressurized components and rotating equipment, respectively.

b. The minimum factors of safety shall be applied.

NOTE 1 See ECSS-E-30 Part 2A, subclauses 4.6.14 through 4.6.16. and ECSS-E-30 Part 3A subclauses 4.7.4.2.7. and 4.7.4.2.8.

NOTE 2 The proof pressure test and the proof spinning test are used to collect evidence of satisfactory workmanship and the quality of material.

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 the materials in contact and mission requirements.

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

   NOTE See AIAA S-080-1998, AIAA S-081-1999.

3. Proof pressure tests for components shall take into account the particular MEOP of the component including transient pressure peaks.

4. All welds in lines and fittings shall be proof tested to at least 1,5 × MEOP and be subject to an additional NDI according to ECSS-E-30-01A subclause 8.1.3, or a safe life analysis shall be performed according to ECSS-E-30-01A subclause 7.2.

NOTE 1 The proof pressure or proof spinning testing may be restricted to component level verification as far as possible.

NOTE 2 See also ECSS-E-30-01A subclause 10.3.

d. The fluid used for the proof pressure test shall be compatible with the structural material in the pressurized hardware.

NOTE See also ECSS-E-30-02, ISO/AWI 14623-2, AIAA S-080-1998, AIAA S-081-1999.

#### 4.6.3.2.3 Characterization under extreme pressure

a. It shall be verified that during a burst test, the interfaces provide a similar stress distribution in the test specimen to that expected under operational conditions.

NOTE Characterization under extreme pressure test serves to demonstrate that the structure survives the extreme loads. One way to demonstrate this is the “burst pressure test”.

b. The qualification test programs shall include a test at burst pressure only for pressure vessels and other pressurized components except for lines and fittings.

NOTE As specified in 4.3.5, the burst pressure exceeds the MEOP × FOS. For FOS, refer to ECSS-E-30 Part 2 and Part 3.

c. The test may be conducted to one of the following states:

1. up to burst;
2. up to the burst pressure specified in the design.

d. For c.2., the design burst pressure shall be maintained for a short time (e.g. at least burn time).

e. For safety reasons,

1. the burst test should be performed with liquids,
2. fluids shall be used that do not pose a hazard to test personnel, and
3. the burst test shall be compatible with the structural material in the pressurized hardware.

NOTE See also ECSS-E-30-02, ISO/AWI 14623-2, AIAA S-080-1998, AIAA S-081-1999.

f. If e.1. is not met, justification shall be provided.

#### 4.6.3.2.4 Testing of bonds

a. To get sufficient confidence in the quality of the bonds, characterization and peel tests shall be performed on samples produced at the same time and under the same conditions as the production item.

NOTE With non-destructive methods, open de-bonds can be identified, however, the bond quality cannot be established presently using these methods.

b. Bonds shall be characterized by establishing the normal tensile and shear strengths under conditions which are representative or equivalent to the nominal functioning conditions of the bond (e.g. tensile rate, pressure, temperature, and humidity).

c. The standard peel test shall be used to establish and compare the quality of the bonds, and propagation of defects.

#### 4.6.3.2.5 Leak tightness

a. During a leak test for operational conditions:

1. The test conditions at the connection should be representative of the operating conditions.

NOTE The operational conditions involve high pressure, hot gas and deformation of the structure under loads. It is difficult to reproduce these conditions during a leak test.

2. The leak shall verify the correct assembly.

b. If a.1. is not met, justification shall be provided.

#### 4.6.3.2.6 Ageing tests

a. As the properties of certain materials can change due to ageing, ageing tests shall be performed on sensitive materials to establish whether ageing affects the qualification.

b. After the tests specified in a., the ageing properties of the materials shall be established.

c. In the accelerated ageing tests, validated correlations between time and temperature shall be used.

NOTE The duration of these tests can be reduced, for instance, by subjecting the materials to storage at elevated temperatures (accelerated ageing tests).

4.6.3.2.7 Safety tests

a. Safety tests shall demonstrate that the product conforms to national and international safety standards conforming to 4.2.e.

b. The procurement shall conform to the national safety standards of the countries where the product is produced, transported or used.

4.6.3.2.8 Firing test

a. When defining the firing test conditions, it shall be taken into account that these conditions are different from the actual flight (e.g. lack of acceleration, different external heating, orientation of the motor, ambient pressure versus vacuum, and mechanical interfaces).

NOTE During the firing test the functioning of the motor is verified. As firing tests are expensive, the number of tests performed is usually limited.

b. The test conditions shall be selected such that a maximum amount of information can be extracted from the test results.

c. The test conditions should be representative of the flight conditions.

d. If c. is not met, justification shall be provided.

### 4.6.4 Verification by inspection

All materials, components, subsystems and systems shall be verified by inspection.

NOTE For inspection see ECSS-E-10-02A subclause 3.1.5.

## 4.7 Production and manufacturing

### 4.7.1 Elements

a. A list of critical events and anomalies during the production shall be established, e.g. temperatures, time, interruption of the production process, pressure.

NOTE For manufacturing of elements see ECSS-Q-20B Clauses 7, 8 and 10, and ECSS-E-30 Part 2A subclause 4.8.

b. All this information shall be provided in the EIDP.

### 4.7.2 Tooling and test equipment

Tooling and test equipment shall be designed to avoid

a. wrong connections,

b. damage of hardware, and

c. pollution or contamination of the hardware.

### 4.7.3 Marking

a. Colour coding for visual identification of the nature of the item according to an agreed standard shall be used and the requirements of ECSS-E–30 Part 6A, subclause 4.11.5.4 shall apply.

NOTE 1 For colour coding for visual identification of the nature of the item, GTPS/SPE/1 can be used.

NOTE 2 For solid rocket motors, this applies to the motor, igniter, initiators and the pyrotechnic transfer lines.

For liquid propulsion systems, this applies to pyrotechnic igniters, solid propellant gas generators and pyrotechnic initiators.

b. All components and sub-assemblies shall have an identification marker that provides information, including:

1. date of manufacturing,
2. expiration date,
3. manufacturers name,
4. type and serial number,
5. deviation or concession reference number.

### 4.7.4 Component manufacturing and assembling

For manufacturing operations refer to the following:

- ECSS-E-30 Part 2A subclause 4.8.6.
- The safety requirements specified in ECSS-Q-20 and ECSS-Q-70.

NOTE For safety requirements see ECSS-Q-40B Clause 4 and subclauses 8.3.1 to 8.3.4, and ECSS-Q-70A subclause 2.5.

## 4.8 In-service

### 4.8.1 General

The in-service requirements cover the period from integration of the propulsion system into the launcher or spacecraft up to and including the disposal of the propulsion system.

For safety, see ECSS-Q-40B Clause 6.

For handling and safety of solid motors, see ECSS-E-30 Part 6A, subclauses 4.8.5, 4.9.3 and 4.11.4.

NOTE As far as handling and safety are concerned, solid motors are considered to be pyrotechnics devices.

### 4.8.2 Operations

a. Before operations (e.g. at the test site, launch facility), the details of the procedures to be applied shall be verified and approved by the facility authorities.

b. The operation procedures shall:

1. take into account the operational limits of the components, subsystems and systems;
2. respect the limited lifecycle of the system and its components.

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

d. At the end of any operation, the propulsion system shall be configured to a safe and operable condition.

e. The operation procedures shall identify any risk to personnel, installations and system.

f. Catastrophic and critical hazards shall be avoided.

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

h. During AIV operations the proper functioning of the measurement equipment shall be verified.

i. The operational procedures shall account for all specific requirements from the planned launch agencies (launcher and launch site).

j. AIV data shall be provided for review purposes.

NOTE See ECSS-M-30-01.

### 4.8.3 Disposal of dangerous products

Disposal of dangerous material shall be performed according to the applicable local regulations and facility rules.

### 4.8.4 Propulsion system operability

#### 4.8.4.1 Verification of the propulsion system operability

a. Measurements and verification activities to ensure that the propulsion system has been properly integrated into the vehicle shall be defined.

NOTE Examples of such activities include leak tests, electrical continuity, functioning of critical equipment.

b. After integration of the propulsion system into the vehicle, the defined measurements and verification activities shall be performed.

c. Any anomaly shall be recorded, investigated and corrected.

#### 4.8.4.2 In-flight operations

##### 4.8.4.2.1 In-flight measurements

a. The in-flight measurements to be performed should be identified at an early stage of the development (project Phases A and B).

NOTE This requirement is important because it enables facilitates similar chains of measurement to be used during ground tests and flight measurements. Because of bandwidth and costs, in-flight measurements on operational systems are limited.

b. To ensure that reliable measurements are obtained that are comparable to those of the ground measurements, in-flight transducers shall be calibrated and compared to the corresponding transducers used during ground tests.

c. Similar chain of measurements should be available for flight measurements and ground measurements.

##### 4.8.4.2.2 Ballistic phase: thermal control

a. It shall be ensured that during the ballistic phases, the temperatures of the propulsion system, including propellants, conforms to the propulsion system requirements.

b. If requested by the thermal analysis, a control system shall be implemented (e.g. thermocouples, heaters, (non-propulsive) venting).

NOTE 1 This is especially important during long ballistic phases.

NOTE 2 Thermal control can be achieved on the stage level by, for example, special devices, proper orientation or the barbecue mode.

c. Thermal analysis shall be reported in accordance with Annex E.

##### 4.8.4.2.3 Ballistic phase: end of mission phase

The consequences for the propulsion system of the end-of-mission phase shall be analysed, including:

a. re-entry, de-orbiting, or re-orbiting;

b. putting the system into a safe mode.

NOTE 1 In certain cases, lower stages are returned by performing special manoeuvres (induce tumbling to increase aerodynamic drag) without using the main engines.

NOTE 2 De-orbiting is performed by manoeuvring the stage and a controlled engine burn.

NOTE 3 In the safe mode, the integrity of the spacecraft or stage is ensured so that debris is not created.

## 4.9 Product assurance and safety

### 4.9.1 General

a. A product assurance and safety policy shall be enforced for the quality, dependability and safety of the propulsion system.

b. Quality assurance, dependability assurance and safety shall be taken into account during the design, development and qualification of the propulsion system.

c. As safety requirements can have a very strong influence on the conceptual design, they shall be taken into account at the start of the design process (project Phases A and B).

NOTE 1 For examples of standards that can be applied, see A.2.

NOTE 2 Safety requirements include, for example, requirements for launch facilities, local and national regulations, and ECSS-Q-40

d. In view of the criticality of the launcher and spacecraft propulsion, which can be a potential single point failure for a mission, dependability assurance shall conform to an agreed standard.

NOTE ECSS-Q-30 can be used for this purpose.

e. To assure the safety of personnel, facilities and equipment, the properties of the system, subsystem and components shall be in accordance with the safety standards conforming to 4.2.e. and national safety regulations.

NOTE For safety, see ECSS-Q-40.

f. If there is a conflict between safety standards and national safety regulations, the latter shall be met.

g. Critical characteristics of materials, components and processes shall be identified.

h. It shall be verified that the critical characteristics of materials, components and processes conform to the system and subsystem requirements, and those derived from the design.

### 4.9.2 Quality assurance system

For the propulsion quality assurance system, see ECSS-Q-20.

## 4.10 Deliverables

### 4.10.1 Documentation

The following documentation, specific to a propulsion system, shall be delivered:

a. Detailed description.

b. Documents demonstrating conformance to the requirements:

1. Performance analysis (in accordance with Annex C),
2. Thermal analysis (in accordance with Annex E),
3. Mechanical analysis,

4. EMC analysis,
5. Functional analysis, including transients (transient analysis in accordance with Annex I),
6. Nozzle flow analysis (in accordance with Annex G),
7. Test report,
8. Dependability analysis,
9. Safety analysis.

c. User manual (in accordance with Annex J).

d. Documents related to product assurance:
   1. FMECA,
   2. Product assurance plan,
   3. Verification control document (VCD).

NOTE Table 1 provides a cross-reference between terms used in this volume to identify project documents and the documents requirements definition (DRD) which specifies the contents of these documents.

### 4.10.2 Document Establishment

Specific documents and the level of detail presented therein shall conform to the system requirements from the documents requirements list (DRL).

## Table 1: Terms used for project documents and the corresponding DRD

| Term used in text | DRD title | DRD reference |
|---|---|---|
| Detailed description | Design definition file | ECSS-E-10 Part 17 [1]<br>ECSS-Q-70 |
| Gauging analysis | Analysis report gauging | Annex D |
| Mechanical analysis | Fracture control analysis<br>Design loads (DL)<br>Dimensional stability analysis (DSA)<br>Fatigue analysis<br>Computer aided design model description and delivery (CADMDD)<br>Fracture control plan and items list<br>Material and mechanical part allowables (MMPal)<br>Addendum: Additional propulsion requirement for "Material and mechanical part allowables" (MMPal)<br>Mathematical model description and delivery (MMDD)<br>Addendum: Additional propulsion requirement for "Mathematical model requirements" (MMR) and "Addendum: Additional propulsion aspects for mathematical model description and delivery" (MMDD)<br>Mathematical model requirements (MMR)<br>Addendum: Additional propulsion requirement for "Mathematical model requirements" (MMR) and "Addendum: Additional propulsion aspects for mathematical model description and delivery" (MMDD)<br>Modal and dynamic response analysis (MDRA)<br>Stress and strength analysis (SSA)<br>Structure alignment budget (SAB)<br>Structure buckling (SB)<br>Structure mass summary (SMS) | ECSS-E-30 Part 2<br>ECSS-E-30 Part 2<br>ECSS-E-30 Part 2<br>ECSS-E-30 Part 2<br>ECSS-E-30 Part 2<br>ECSS-E-30 Part 2<br>ECSS-E-30 Part 2<br>Annex L<br>ECSS-E-30 Part 2<br>Annex M<br>Annex N<br>ECSS-E-30 Part 2<br>Annex M<br>Annex N<br>ECSS-E-30 Part 2<br>ECSS-E-30 Part 2<br>ECSS-E-30 Part 2<br>ECSS-E-30 Part 2<br>ECSS-E-30 Part 2 |
| Performance analysis | Propulsion performance analysis report (AR-P) | Annex C |
| Performance analysis | Addendum: Specific propulsion aspects for material and mechanical part allowables (MMPal) | Annex L |
| Plume analysis | Plume analysis report (AR-Pl) | Annex F |
| Nozzle flow analysis | Nozzle and discharge flow analysis report (AR-N) | Annex G |
| Sloshing analysis | Sloshing analysis report (AR-S) | Annex H |
| Thermal analysis | Applicable DRDs in ECSS-E-30 Part 1<br>Addendum: Specific propulsion aspects for thermal analysis | ECSS-E-30 Part 1<br>Annex E |
| Mathematical analysis | Addendum: Specific propulsion aspects for material and mechanical part allowables (MMPal) | Annex L |
| Thermal model | Addendum: Specific propulsion aspects for material and mechanical part allowables (MMPal) | Annex L |
| Transient analysis | Propulsion transients analysis report (AR-Tr) | Annex I |
| Test documentation | AIV (Test plan)<br>Test procedure<br>Test report<br>Test specification | ECSS-E-10-02<br>ECSS-E-10-02<br>ECSS-E-10-02<br>ECSS-E-10-02 |
| Verification | Verification Control Document | ECSS-E-10-02 |
| RAMS | Dependability<br>Safety | ECSS-Q-30<br>ECSS-Q-40 |

**Table 1: Terms used for project documents and the corresponding DRD** *(continued) (continued)*

| Term used in text | DRD title | DRD reference |
|---|---|---|
| FMECA | FMECA | ECSS-Q-30-02 |
| User manual | Propulsion subsystem or system user manual (UM) | Annex J |
| Product assurance plan | Product assurance plan | ECSS-Q-00 |
| 1. DRDs ECSS-E-10 Part 17 to be published. | | |

# 5

# Solid propulsion for launchers and spacecraft

## 5.1 General

Solid propulsion is suitable for launchers as a propulsion system with one or more stages as boosters (strap-on or main). In addition, solid propulsion is especially appropriate for separation and de-orbit motors for stages and boosters.

As solid propulsion thrusters can only deliver their total impulse in one firing, solid propulsion on spacecraft is used only for:

- orbit change (e.g. apogee or perigee manoeuvre);
- impart accelerations (e.g. liquid re-orientation manoeuvres, separation manoeuvres).

A solid propulsion system comprises the following main subsystems.

- The gas generating system consisting of
  - a solid propellant grain contained in;
  - a thermally protected case.
- A nozzle with or without TVC.
- An ignition system to ignite the solid propellant.

Solid propulsion systems can either deliver a velocity increment in a fixed direction (with respect to the launcher or spacecraft) or in a variable direction, depending on whether TVC is present or not. Most solid propulsion systems use a single nozzle and roll control is usually provided by a separate system. Solid propulsion systems are “one-shot” systems and do not need a lot of preparation before use.

This Clause 5 applies to large and small systems; the latter usually have some different requirements to the large systems.

The requirements for the design, verification and constraints for ignition chains are defined in ECSS-E-30 Part 2.

## 5.2 Mission

The solid propulsion system shall conform to the mission requirements for the following:

a. pre-launch activities (storage, ageing before use, transport, integration and waiting on the launch pad);

b. launch;

c. separation from the launcher;

d. flight;

e. in-flight operations;

f. de-orbiting.

## 5.3 Functional

### 5.3.1 Steady state

a. The propulsion system shall:

1. Conform to the interfaces (see 5.5).
2. Provide the specified total impulse, a thrust profile (nominal and dispersion) versus time.

b. The overall thrust profile shall be defined, taking into account the following launcher or spacecraft system constraints:

1. The general loads on the launcher or spacecraft (due to aerodynamics, thermal fluxes and guidance or attitude control).
2. The induced accelerations.

c. To conform to a. and b., the following aspects shall be covered:

1. levelthrust level and orientation versus time;
2. burning time;
3. total impulse;
4. reliability level.

### 5.3.2 Transients

The initial and final transient thrusts shall conform to the lift-off and separation constraints and requirements.

### 5.3.3 End-of-flight mass

The mass of the motor shall

a. be taken into account, and

b. conform to the system requirements.

NOTE The "end-of-flight" mass of solid motors strongly depends on the internal ballistics, functional parameters and the applied technologies.

### 5.3.4 First stage

As the thrust profile of the first stage (or main boosters) has a very strong effect on the overall launcher configuration and performance, the first stage configuration and thrust profile shall be thoroughly analysed and a trade-off made against system constraints and requirements.

### 5.3.5 External loads during the complete life of the propulsion system

All external loads, static and dynamic (including mechanical, thermal, electrical, magnetic, humidity and radiation) shall be specified and taken into account.

### 5.3.6 Electrical

The propulsion system shall have electrical continuity, including grounding.

### 5.3.7 Thrust orientation

The propulsion system shall provide TVC or a thrust in a fixed orientation (with respect to the launcher or spacecraft) according to the system requirements.

## 5.4 Constraints

### 5.4.1 General

The interfaces, operational requirements, disposal, cost and potential evolution, environmental impact, availability, ground tests, and national and international safety regulations impose constrains which affect the propulsion system.

### 5.4.2 Operational constraints

#### 5.4.2.1 Induced and environmental temperature

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

b. The temperature range during the mission shall be

   1. specified, and
   2. in accordance with the technical realization of the motor and the thermal control system.

c. The number and amplitude of the temperature variations (thermal cycling) during the motor life shall be specified.

d. Active or passive thermal control shall ensure that:

   1. the temperature of the solid motor remains within the specified limits,
   2. the amplitude and the frequency of the temperature variations remain within the limits specified for the motor.

      NOTE This requirement is especially important for motors which have a long in-orbit life before being operated.

#### 5.4.2.2 General environment

a. The motor shall comply with the specified and its self-induced loads (thermal, dynamic) environment.

b. Sensitive measurement and control devices shall be protected against adverse effects.

#### 5.4.2.3 Ageing

The ageing requirements shall be specified.

### 5.4.3 Special constraints

#### 5.4.3.1 Oscillatory combustion

Vibration levels resulting from oscillatory combustion shall be specified at system and subsystem level.

#### 5.4.3.2 Safety

a. To minimize the risk of catastrophic failures, the solid propellant motor shall conform to the requirements on safety analysis.

   NOTE See ECSS-Q-40.

b. Life motors shall be marked as such (see 4.7.3).

#### 5.4.3.3 Thrust centroid time

a. For small motors that operate for very short operation times (e.g. less than 1 s), or small motors that operate in pairs, the thrust centroid time and

impulse bit or total impulse and operating time shall conform to the spacecraft subsystem and system requirements.

b. The thrust centroid time and impulse bit or total impulse and operating time shall be characterized.

## 5.5 Interfaces

### 5.5.1 General

All interfaces shall conform to the propulsion system requirements during the whole life of the system or subsystems and include the following:

a. Other stages of the launcher.

b. The launcher or spacecraft spaceonics.

c. Stage or spacecraft components:

1. skirts;
2. spaceonics (including hardware, OBDH, TM/TC, wiring and tunnels);
3. separation devices;
4. TVC;
5. stage or spacecraft thermal protection;
6. contamination (e.g. plume effects);
7. termination and destruction devices;
8. environmental protection devices (e.g. rain, dust, and Sun).

d. The nature of the interfaces, i.e.:

1. geometry, including the analysis of the dimensions for all phases of life (e.g. assembly or AIV, transport, integration on the spacecraft and flight);
2. mechanical, including induced loads, static and dynamic;
3. thermal, including thermal fluxes;
4. electrical, including ensuring continuity, ESD and EMI;
5. materials, including ensuring compatibility

   NOTE Refer to ECSS-E-30 Part 8.

e. Interfaces with GSE and transport, including:

1. definition of interfaces:
   (a) for launcher or spacecraft GSE and transport,
   (b) with the launch authorities for safety;
2. capability for the electrical grounding of the systems and subsystems.

### 5.5.2 Reporting

The plume analysis specified in 5.5.1.c.6. shall be reported in accordance with Annex F.

## 5.6 Design

### 5.6.1 Overview

The design phase comprises the overall definitions of the concept of the system and subsystem, its architecture and its associated technical solutions.

Solid rocket motors provide a cost effective, reliable and safe means for launcher or spacecraft propulsion. The solid motor can be prepared well in advance of the launch, reducing the number of pre-launch activities on the launch pad compared to liquid propulsion.

Contrary to liquid propulsion systems, the solid propulsion system contains all the propellant in the combustion chamber of the motor. Therefore, the dimensioning is determined by the internal loads of the solid motor. The grain design determines the thrust profile. For this reason, the design of the grain and the whole motor is highly interactive with the overall system requirements.

For solid motors the actual test firing cannot be performed with the flight engine as these motors are "one-shot" items.

## 5.6.2 Propulsion system selection and design process

### 5.6.2.1 General

a. In order to conform to the mission requirements within the restriction of feasible technical solutions, an interactive pre-design process between the propulsion design team and mission specialists shall be performed.

b. Motor and subsequent component level requirements shall be derived from the results of the pre-design process specified in a. and the system requirements.

c. All components of a solid rocket motor shall:

   1. demonstrate compatibility with the selected materials, propellants and fluids;
   2. be selected taking into account safety, economics, reliability and environmental considerations and restrictions (e.g. debris, pollution).

   NOTE The main components of a solid rocket motor are:

   - the propellant grain,
   - the motor case,
   - the internal thermal protection and liner,
   - the nozzle with or without the possibility of thrust vectoring,
   - the igniter.

d. If there are stringent requirements on reproducibility, the causes for potential dispersions shall be analysed in the pre-design phase (project Phases A and B).

e. The pre-design of the solid motor shall take into account the following aspects:

   1. the mass and COM of the propulsion system;
   2. performance;
   3. type of ignition system;
   4. nozzle structure and configuration (e.g. thrust orientation);
   5. propellant type.

   NOTE If the requirements cannot be met, (e.g. target cost and industrial feasibility) either:

   - the requirements are re-considered,
   - the system or subsystem design modified, or
   - the manufacturing and control processes modified (see ECSS-E-10 Part 1).

### 5.6.2.2 Propellants

The choice of propellant shall be based on the mission requirements, interface with other systems or subsystems, lifetime, safety, availability, manufacturing process, performance, cost and environmental considerations and restrictions (e.g. pollution).

#### 5.6.2.3 Grain design

a. The selection of the type of grain shall be based on a trade-off between the following:
   - conformance to the requirements on the thrust profile (see subclause 5.3),
   - the availability of technology,
   - economics,
   - mechanical properties,
   - behaviour and internal ballistics.

b. The grain design shall be defined.

#### 5.6.2.4 Material selection

As thermal protection materials, propellants and liner-primer materials often contain liquids to adjust their properties, they shall be selected to ensure that, during the mission, the migration of these liquids does not change the properties of any material (mechanical, thermal, ballistic) or their bonding in an unacceptable way.

NOTE Primer materials are often used to obtain a good adherence between thermal protection and the propellant.

### 5.6.3 Development process

#### 5.6.3.1 Reporting

The reporting shall be in accordance with Annex G.

#### 5.6.3.2 General

As firing tests cannot be performed on the actual flight motor (one-shot item), the development of solid propulsion systems is performed in such a way that it results in a very well designed and well reproducible product.

#### 5.6.3.3 Development logic

a. During the development phase the following objectives shall be completed:
   1. To arrive at, establish, justify and freeze the design of the solid propulsion system.
   2. To establish all the characteristics of the system or subsystem and components.
   3. To establish the manufacturing and control processes.

      NOTE The objective is to arrive at a product meeting the maximum acceptable specified product-to-product variation while conforming to the functional, performance and system requirements.

b. In order to establish and freeze the design:
   1. the sizing process shall be executed;
   2. verification models shall be established,
   3. mathematical modelling shall be reported in accordance with Annex K.
   4. validation and verification tests shall be performed.

c. The testing, analyses and experience should identify the possible failure modes.

d. If c. is not carried out, justification shall be provided.

e. All unacceptable failure modes shall be avoided by design.

f. A FMECA according to an agreed standard shall be made.

NOTE 1 ECSS-Q-30-02 can be used for this purpose.

NOTE 2 The development program strongly depends on the size, the level of applied technology, specific requirements and intended use of the propulsion system.

g. The characteristics of the systems, subsystems and components shall be established from analyses, characterization of materials, test results and correlation with models.

h. The manufacturing and control processes shall be established, described and justified for the critical technologies.

i. It shall be demonstrated that the manufacturing and control processes lead to products that satisfy the specified maximum product-to-product variation, while conforming to the system requirements.

j. The propulsion system should be verified by analysis or testing.

k. If j. is not met, justification shall provided.

l. Where knowledge of margins is specified, while these margins cannot be obtained by analyses or standard tests, materials, components or subsystems shall undergo limit testing.

## 5.6.4 Design at propulsion system level

### 5.6.4.1 Reporting

The reporting shall be in accordance with Annex C.

### 5.6.4.2 Global performances: mass flow rate

The mass flow rate history shall be determined.

NOTE The mass flow rate history cannot be determined without knowing, as a minimum, the nozzle erosion history and the pressure history.

### 5.6.4.3 Global performances: characteristic velocity - losses and gains

#### 5.6.4.3.1 Kinetic effects

The main effect is incomplete combustion, especially the incomplete combustion of metal additives.

The effect of finite chemical kinetics can be estimated by taking into account the dimensions of the combustion chamber, using a kinetic calculation, and the same reactions and species used in the ODE-type calculation, provided that the kinetic data is available.

An alternative approach is to use experimental data on the performance of similar engines.

The characteristic velocity is represented by $C^*$.

#### 5.6.4.3.2 Alumina deposition

a. The amount of alumina accumulated in the base of the motor shall be estimated.

NOTE In solid motors which use aluminium in the propellant and which have submerged nozzles, substantial amounts of alumina ($Al_2O_3$) can accumulate in the base of the motor. This has three effects:

- it increases the inert mass of the motor,
- it reduces the mass flow rate through the nozzle,

- it increases the $C^*$ as compared to ideal conditions because the mass flow rate has been reduced with respect to the ideal mass flow rate.

b. The estimate specified in a. should be based on experience.

c. If b. is not complied with, justification shall be provided for the estimate.

d. The effects on $C^*$ and mass flow rate shall be taken into account.

e. The effect on the increase of inert mass of the motor shall be taken into account in the system performance analyses.

NOTE In solid motors with a high spin rate, alumina may accumulate at the sides of the motors and may lead to similar effects.

5.6.4.3.3 Thermal protection

a. For a motor with a long end burning grain, the amount of consumed thermal protection expelled during the motor operation shall be estimated.

NOTE The gasification – erosion of the thermal protection has the following effects:

- Increase in the mass flow rate compared to the propellants mass flow rate.
- Change of the composition of the gases in the combustion chamber, and usually, lowering of the combustion temperature slightly.

Usually, these effects are small, except for end burning grains.

For long end burning grains, substantial amounts of thermal protection are consumed and ejected from the motor. If this is not properly accounted for, this can easily lead to large errors in the $C^*$ and hence, in the specific impulse.

b. The amount of consumed thermal protection expelled during motor operation specified in a. shall be taken into account in proportion to the propellant when determining the theoretical values for $C^*$.

c. To determine the $I_{sp}$, the ejected mass due to the thermal protection shall also be considered.

NOTE $I_{sp}$ is calculated using the expression:

$$I_{sp} = \frac{\int_0^{t_b} F dt}{(M_p + M_{pt})}$$

where
$M_p$ is the mass of the propellant grain,
$M_{pt}$ the mass of the ejected (consumed) thermal protection.

### 5.6.4.4 Global performances: thrust coefficient - losses

5.6.4.4.1 Overview

In addition to subclause 4.3.2.5.2, subclauses 5.6.4.4.2 to 5.6.4.4.5 apply.

The thrust coefficient is represented by $C_F$.

5.6.4.4.2 Shocks

Shocks can be induced due to nozzle contouring or to different local erosion rates affecting the nozzle contour. In a well-designed nozzle, shock effects are negligible and can be estimated mainly by experience and by similarity analysis.

5.6.4.4.3 Nozzle erosion

As nozzle erosion affects the thrust coefficient due to the changing expansion ratio during firing and the change in the nozzle contour, these effects shall be taken into account.

5.6.4.4.4 Two-phase flows

a. For the nozzle contour:

1. The upper limit of the effect of the impact of particles on the nozzle exit contour shall be analysed and established.
2. It shall be ensured that the effect of the impact of particles on the nozzle exit contour is below the limit specified in 1.

NOTE 1 Droplets and particles in the flow originate from metal combustion. Their main effect on performance is a drag effect, reducing the effective exhaust velocity.

NOTE 2 The nozzle performance strongly depends on the shape of the nozzle extension.

b. In evaluating nozzle performance, it shall be ensured that a particle size distribution is used that represents the particle size distribution of the propellant after combustion for all cases of combustion and flow processes.

NOTE Adjusting the nozzle shape to reduce the effect of particle impact on the nozzle leads to reduced fluid dynamic nozzle efficiency.

5.6.4.4.5 Nozzle entrance conditions: overview

The flow conditions at the nozzle entrance can deviate substantially from the standard 1-D flow assumption for assessing the $C_F$. This can be caused by, for example, special grain configurations or nozzle submergence.

5.6.4.4.6 Nozzle entrance conditions: estimation of flow conditions

If there is the danger of severe deviations in the assessment of $C_F$ due to the flow effects described in 5.6.4.4.5, these effects shall be estimated by one of the following means:

- analysis,
- empirical correlations,
- tests, or
- a combination of the above.

### 5.6.4.5 Transient phases: ignition transient

5.6.4.5.1 Overview

The ignition phase is the phase between $t$=0 and $t$=$t_{ign}$, where $t_{ign}$ is the ignition time, i.e. the time at which the motor pressure has reached a certain percentage of the theoretical pressure corresponding to the combustion of the main propellant only (explicitly excluding the igniter peak).

The time at which the pressure in the motor starts to build up (slope change) due to the combustion of the main propellant is called $t_i$.

5.6.4.5.2 Transient analysis

A transient analysis shall be performed and reported in accordance with Annex I.

5.6.4.5.3 Ignition phase

a. During the ignition phase:

1. the slope of the pressure shall remain between a specified minimum and maximum slope;
2. the time at which the combustion starts, $t_i$, shall be within the specified minimum and maximum values.

b. The percentage of the theoretical pressure defining $t_{ign}$, shall be defined in the motor or system specification.

5.6.4.5.4 Motor ignition

The ignition pressure history shall be calculated for the period $t$=0 until quasi steady motor operation has been achieved.

NOTE In the preliminary design, phase simplified methods (0-D) can be used if the time of the beginning of the ignition, $t_i$, and the duration of the flame spreading over the complete grain are known. This data is usually obtained by experience or specific tests.

If it is specified in the ignition requirements, or the results of the simplified analysis are not considered satisfactory, a more detailed analysis is performed.

#### 5.6.4.6 Transient phases: maximum chamber pressure due to ignition

a. The operating time of the igniter shall exceed the ignition time, $t_{ign}$.

NOTE This can result in a $\hat{p}_{max}$during ignition.

b. The pressure $\hat{p}_{max}$ shall be used as the dimensioning pressure for the grain.

c. If the pressure $\hat{p}_{max}$ is also the absolute maximum pressure during the mission, it shall be used for structural dimensioning.

d. The chamber pressure due to the igniter peak shall not exceed $\hat{p}_{max}$.

#### 5.6.4.7 Transient phases: tail-off

5.6.4.7.1 General

During the tail-off phase the thrust is low but the requirements on the dispersion in thrust are strict. This is specially the case if two or more boosters operating in pairs, or if the burn-out of a motor or stage is followed by a stage separation and ignition of a subsequent stage.

5.6.4.7.2 Normative provisions

For the cases described in 5.6.4.7.1 the following apply:

a. The maximum dispersion in tail-off shall be specified at system or subsystem level.

b. The grain design shall:
   1. take the requirements on dispersion in thrust into account, and
   2. ensure that the thrust during tail-off conforms to these requirements.

c. As conformance to the tail-off requirements may strongly affect the motor and grain design, requirements a. and b. shall be taken into account early in the design (project Phases A and B) with well validated methods covered in standards conforming to 4.2.e.

#### 5.6.4.8 Contamination

a. The motor shall be protected against contaminants entering the motor.

b. For composite propellants, which are usually hygroscopic, it shall be ensured that moisture does not affect the propellant.

#### 5.6.4.9 Detonation risk

It shall be demonstrated that failures in the motor shall not lead to detonation.

#### 5.6.4.10 Testing

a. The motor shall be in a state to undergo static test firing.

b. Test results shall be used for the engineering activities for the development and qualification of the motor.

NOTE In general, there are three objectives for testing the motor:

- To verify that the motor conforms to the subsystem and system requirements (see 5.8.3).
- To collect accurate characteristic motor data for the detailed description.
- To obtain additional information (e.g. dynamic structural behaviour).

#### 5.6.4.11 Electrical continuity

Electrical continuity shall be ensured.

#### 5.6.4.12 Leak tightness

The motor shall conform to the requirements on leak tightness during the mission life.

NOTE 1 Most solid rocket motors for space propulsion are stored under internal pressure. Monitoring the pressure provides an indication of whether the leak tightness requirements are being met.

NOTE 2 Very small motors may undergo leak testing by means of external He pressurization and subsequent He-detection in the motor pressurant gas (helium leak test).

#### 5.6.4.13 Interfaces and connections

a. Internal interfaces and connections shall be defined and justified at the motor level.

b. It shall be ensured that the quality of bonding is in accordance with a standard conforming to 4.2.e.

NOTE For requirements on bonding, see 5.6.4.15.

#### 5.6.4.14 Pollution

The motor shall conform to the requirements on pollution (e.g. ejection of alumina or particles into the environment).

#### 5.6.4.15 Bonding

##### 5.6.4.15.1 Overview

For bonding, see PSS-03-210.

##### 5.6.4.15.2 General

a. If the primary aim of a bond is to transmit forces, it shall be ensured that shear and compression forces primarily load the bond.

b. If the primary aim is to keep two materials in contact with each other, the bond may be loaded under tension.

NOTE Cold bonding takes place at room temperature. In hot bonding, at least one of the interfacing materials polymerizes at elevated temperatures.

c. For reliability reasons, hot bonding should be used.

d. It shall be ensured that if a bonded connection fails under loads the rupture shall be in one of the bonded materials, and not in the interface (cohesive rupture).

e. To assure cohesive rupture the following apply:

1. Adhesives and processes shall be properly selected for the envisaged bonds, in accordance with a standard conforming to 4.2.e.

   NOTE For the selection of adhesive and processes, see PSS-03-210.

2. Cleanliness shall be maintained and precautions taken to ensure that there is no contamination or pollution of the surfaces to be bonded, in accordance with a standard conforming to 4.2.e. and PSS-03-210.

3. For the mission life, the effects of ageing, migration of liquids (see 5.6.5.3.4) and humidity shall be taken into account.

4. Strict control of process conditions (e.g. humidity, temperature) shall be maintained during manufacturing, in accordance with a standard conforming to 4.2.e. and PSS-03-210.

#### 5.6.4.15.3 Bonding on solid motors: overview

Bonding is used on:

- the motor case (internal and external);
- the internal thermal protection system;
- the propellant grain;
- the nozzles (internal and external), including the flexible seal;
- the igniter.

As far as bonding is concerned, the igniter is regarded as a (small) solid rocket motor.

If two rigid components are bonded, which are subject to deformation during the mission, usually a deformable or compressible material (rubber) is applied at the interface of the rigid components. The components are both bonded to the rubber interface. Typical examples of such components are the integrated skirt and the polar bosses in composite motor cases.

#### 5.6.4.15.4 Bonding on solid motors: motor case external

a. For components that are bonded to the outside of the motor case (e.g. raceway, electrical equipment, pyrotechnic devices, measurement equipment, external thermal protection, metal foil to ensure electrical continuity), cold bonding may be applied.

b. It shall be ensured that the process is properly controlled (e.g. humidity, temperature, cleanliness) during bonding, in accordance with a standard conforming to 4.2.e. and PSS-03-210.

#### 5.6.4.15.5 Bonding on solid motors: internal bonds

a. In order to limit stress concentrations to acceptable values, at termination (triple) points, specific measures such as floaters, grooves, and additional layers of bonding material, shall be applied.

b. For all bonds that function in a hot gas environment, it shall be ensured that there is no abutting debond.

5.6.4.15.6 Bonding on solid motors: nozzle

a. Bonds shall retain their integrity during the mission.

b. Degradation of bonds that are not subjected to severe loads and have no requirements on gas tightness may be accepted.

NOTE In the nozzle three types of bonds are used:

- Bonds that are not subjected to severe loads and have no requirement on gas tightness. These bonds basically serve to facilitate manufacturing and integration. Degradation of these bonds during the mission can be accepted (e.g. bonding between the throat insert and thermal protection).
- Bonds that are not subjected to severe loads but ensure gas-tightness (e.g. thermal protection of the flexible joint).
- Bonds that are subjected to severe loads and sometimes also ensure gas tightness (e.g. bonds between shims and rubber in the flexible joints and the structural parts of the nozzle extension).

5.6.4.15.7 Bonding on solid motors: sizing

a. The complete mission shall be taken into account to establish which of the following conditions determine the criteria for sizing:
   - motor operation,
   - storage (at minimum or maximum temperature),
   - transport (at minimum or maximum temperature),
   - the manufacturing process.

b. For internal bonds (thermal protection) the same criteria as in 5.6.5.3.11 shall be taken into account for dimensioning.

c. To prevent failure, the strength of bonds shall be analysed by comparing the equivalent uni-axial load ($\sigma_N$, $\tau$) to the experimental strengths of such bonds (at equivalent load rates and temperatures).

#### 5.6.4.16 Imbalance

5.6.4.16.1 General

In addition to subclause 4.3.7, subclause 5.6.4.16.2 applies to solid motors.

5.6.4.16.2 Non-stable spinning

As solid motors may be spin-stabilized to eliminate the effects of thrust misalignment, it shall be ensured that the inertial and geometric properties during motor operations are such that the rotational motion is stable.

### 5.6.5 Solid rocket motor

#### 5.6.5.1 Motor case

5.6.5.1.1 Main functions

The main functions of the motor case are:

- To mechanically withstand the internal pressure due to the combustion of the propellant and the loads on the motor during the mission (handling, storage, preparation for flight, integration, flight, life in orbit, in orbit operation and disposal).
- To contain the propellant and enable the load of the propellant.

- To enable the mounting of the components and subsystems.
- To connect the systems, subsystems and the spacecraft or launcher.
- To transfer forces and moments.

5.6.5.1.2 Material selection

a. In selecting the materials a trade-off shall be made taking into account the available technologies, experience, economics and the intended use.

b. Corrosion protection shall be taken into account for metal parts.

NOTE The selection of materials and the technologies to be applied to the manufacture of the motor case are important as these have a very large effect on the inert mass of the case and the way in which the case interfaces with the propulsion system and components.

c. Two fundamentally different solutions may be applied:

1. Metallic cases

NOTE These type of cases have the advantage that they can be easily made leak tight, also for connections to other components (internal or external, skirts, connectors, fixation points).

2. Composite material motor cases

NOTE 1 These are made from fibres (e.g. aramide, carbon) impregnated with a polymer material (usually epoxy resin). These cases are made by filament winding and sometimes reinforced by layers of fibres or fibre cloth (tow placement) (e.g. skirt, case). They have, for the same loads, a much smaller inert mass than metallic cases. As these cases are not naturally leak tight, leak tightness can be achieved only with special provisions, for example, internal insulation.

NOTE 2 For solid motors that are intended to stay in orbit for prolonged periods (e.g. de-orbiting motors and motors for interplanetary space flight), there are the following specific concerns:

- outgassing;
- thermal cycling;
- ageing;
- degradation due to radiation.

d. The motor case shall conform to the outgassing requirements in ECSS-Q-70-01A subclause 6.7 and ECSS-Q-70-02A subclause 7.2.

5.6.5.1.3 General dimensioning

a. The dimensioning of the motor case shall be in conformance to the mission, launcher, booster or spacecraft and motor requirements taking into account the combinations of loads that occur during the mission, and the specified factors of safety.

b. The thermal and mechanical loads and interface geometries during propellant casting and curing shall be taken into account.

NOTE The dimensioning, except for the integrated skirt (see 5.6.5.1.4) is, in most cases, determined by the internal pressure of the motor during operation.

c. The maximum expected operating pressure (MEOP) shall:

1. be determined at the maximum expected burning rate according to the conditions of the extreme envelope;
2. include the expected nominal pressure deviations ($n\ \sigma$), $n$ being in accordance with the reliability target.

d. For the dimensioning, a burst pressure of $p \geq 1{,}25 \times$ MEOP shall be used.

e. For metallic cases the yield pressure shall satisfy: $p_{yield} \geq 1{,}15 \times$ MEOP.

f. During the development phase, there it shall be verified and ensured that the MEOP is in accordance with the internal ballistics of the motor.

g. For long combustion chambers, the front-end pressure shall be taken to establish the MEOP.

h. Elements that are connected to the case (e.g. skirts, mounting parts and interface connectors) shall be dimensioned by accounting for the combination of forces due to internal pressure and other forces such such as external loads, inertial forces and local loads.

i. Thermal loads shall be taken into account, including the thermal effects on the material characteristics.

##### 5.6.5.1.4 Integrated skirt

The choice of the skirt design shall be based on the following:

a. System and subsystem requirements.

b. The possibility of attaching the skirt to the motor case itself, accounting for case deformation due to internal pressure.

c. The ability to transfer forces and torques.

NOTE Usually, a (part of the) skirt is integrated with the case to enable the motor to be connected to the spacecraft, launcher or booster or other systems and subsystems and to transfer forces. The skirt can be metallic or made from composite materials and it can be different from the case materials.

d. Visco-eleastic and visco-plastic properties of materials shall be reported according to Annex M.

#### 5.6.5.2 Thermal insulation, liner and bonding

##### 5.6.5.2.1 Main functions

The main functions of the thermal protection (insulation) are as follows:

- To protect the motor case from the hot combustion gases and to keep the heating of the motor case within the specified limits.
- To inhibit the specified parts of the grain, so that the burning surface develops according to the envisaged burning surface history.
- To ensure leak tightness of the case (for composite material cases).
- To enable the proper transfer of the loads during the various thermal expansions of the case and the grain.
- To transfer the loads between the grain and the case during the whole mission (e.g. acceleration, ignition).

The thermal protection can, for certain configurations, also contribute to the stress relief in the grain (e.g. during ignition and thermal deformation).

#### 5.6.5.2.2 Material selection

a. General

1. In selecting the material for the thermal protection, as a minimum, the following shall be taken into account:
   (a) thermal properties;
   (b) ablative properties;
   (c) mechanical properties;
   (d) bonding characteristics;
   (e) leak tightness characteristics;
   (f) the manufacturing procedures and processes;
2. Visco-eleastic and visco-plastic properties of materials shall be reported according to Annex M.
3. To select the best possible material, a trade-off shall be made in view of the aspects given in a.1., economics and the motor requirements (see 5.6.2).

b. Determination of the ablative properties

If no detailed information is available on the ablative properties of the thermal protection material, the ablation rate shall be determined in small test motors that accurately reproduce the conditions that are expected in the flight motor (e.g. mass-flux, velocity of combustion gases, pressure, gas temperature and composition, and duration of exposure to hot gases).

c. Technology

1. The interactions of the technologies used to apply the thermal protection with the requirements, the production and integration process, and the motor and grain configuration shall be taken into account when selecting the technology.

   NOTE The most important techniques are:
   - bonding of the thermal protection to the grain;
   - bonding of the thermal protection to the case;
   - filament winding of the case on the thermal protection which is placed on the mandrel followed by a polymerization;
   - internal spraying of the thermal protection on the case.
2. If pieces of thermal protection are bonded together, it shall be ensured that no ruptures or debonds occur.
3. For all cases, it shall be ensured that:
   (a) the surface of the thermal protection is in a good condition for subsequent bonding;
   (b) the materials and processes are compatible with the propellant and motor case, and qualified for the application.

#### 5.6.5.2.3 Outgassing

For solid motors for spacecraft, the thermal protection shall conform to the outgassing requirements in ECSS-Q-70-01A subclause 6.7.1.a and ECSS-Q-70-02A subclause 7.2, after burn-out of the motor.

#### 5.6.5.2.4 Dimensioning of the thermal protection

a. The following variables shall be taken into account when dimensioning the thermal protection system:

1. the specified temperature of interfaces;
2. the configuration of the floater;

3. the ablation rate of the thermal protection;
4. the exposure time and potential pre-heating;
5. the factors of safety to be applied;
6. the magnitude of the internal fluxes

NOTE The thickness of the thermal protection (which is not usually constant) depends on the previous variables.

b. "Pre-heating" shall be taken into account in the dimensioning of the floater and inhibitor areas.

c. As preheating can be different in flight and ground test-conditions, the worst cases shall be determined.

d. The connection of the thermal protection to floater shall be designed such that stress concentrations are reduced.

e. For the design of the thermal protection it shall be ensured that:

1. The temperature of the interface between the thermal protection and the propellant are such that there is no risk of auto-ignition of the propellant due to an interface temperature that is too high.
2. The propellant pre-heating through the floater does not exceed the specified values.

f. After having dimensioned the thermal protection on thermal loads and ablation, it shall be verified that the dimensioning satisfies the mechanical requirements (i.e. expansion-contraction and transfer of loads, see also g. and h.) during the whole mission.

NOTE The constraints on the thermal protection are due to deformations of the case and the grain, and include the following:

- storage conditions;
- manufacturing process;
- loads during flight (e.g. pressures and accelerations).

g. To evaluate the mechanical behaviour of the thermal protection, finite element analyses may be applied to assess the critical areas: floater, interface thermal protection-grain and interface thermal protection-case.

h. The mechanical properties of the thermal protection and the bonds to be used in the analyses specified in g. shall be based on either available test data, or on data available on the propellant, thermal protection material, case material and bonding material and processes.

i. Visco-eleastic and visco-plastic properties of materials referred to in g. and h. shall be reported according to Annex M.

j. Thermal analysis shall be reported in accordance with Annex E.

k. The demonstration of the appropriateness of the analysis codes for f., g. and h. shall be in accordance with Annex N.

#### 5.6.5.3 Propellant grain

##### 5.6.5.3.1 Overview

The grain geometry, together with the nozzle and the propellant burning rate, which depends on the operating pressure, determines the mass flow rate and pressure history. Two cases are considered:

- Case-bonded grains

NOTE For case-bonded grains there is a thermal protection (insulation) between the case and the grain. The thermal protection, is first applied to the case, or the case to the

thermal protection, after which the propellant is cast into the insulated motor case.

- Free-standing grains

  NOTE Free-standing grains are usually inhibited on the outside, while the case has an internal thermal protection. The grain is held in position by mechanical means, so that the forces between the case and the grain can be transferred.

5.6.5.3.2 General

a. The pressurization of the grain, including the pressurization of the gaps between the grain and the case and the effect on the grain stresses shall be analysed.

b. It shall be ensured that, if there is circulation of hot gas, this does not lead to inadvertent ignition of the insulated parts of the grain.

c. For large motors, the case-bonded solution should be used.

d. Visco-eleastic and visco-plastic properties of the grain shall be reported according to Annex M.

5.6.5.3.3 Main functions and constraints

a. The following are the main functions to be performed by the propellant grain:
   1. It shall provide the specified impulse for the propulsion.
   2. It shall provide the mass flow rate of combustion products according to the specified mass flow rate history.
   3. The propellant grain shall withstand the mechanical and thermal loads during the mission and manufacturing.

b. The following are the main constraints to be conformed to by the propellant grain:
   1. It shall be compatible with the case and the thermal protection system and a movable nozzle, if present.
   2. It shall be compatible with the ignition system and the associated ignition process.
   3. It shall be compatible with the (internal and external) environment (e.g. humidity and materials).
   4. It shall be compatible with the (envisaged) manufacturing methods and procedures.
   5. It shall conform to the (national) safety requirements.

c. Visco-eleastic and visco-plastic properties of the grain shall be reported according to Annex M.

5.6.5.3.4 Material selection

The choice of the propellant is based on the following requirements:

a. It shall conform to the system performance requirements (e.g. $I_{sp}$ and density).

b. The ballistic and mechanical properties of the selected propellant shall be in conformance to the mission requirements and solid rocket motor design.

c. It shall be ensured that the characteristics of the selected propellant are well-known for the mission conditions and have good ageing characterisitics.

d. The materials shall be selected to be in accordance with the selected manufacturing process, reliability requirements, grain geometry and costs.

5.6.5.3.5 Ballistics: dimensioning

For the ballistic dimensioning of the propellant grain, the pressure and mass flow rate histories shall be determined, in conformance with the system and subsystem requirements, according to the throat design (i.e. dimensions and erosion).

NOTE 1 This affects:

- dimensioning of the case (MEOP);
- dimensioning of the internal thermal protection (e.g. exposure time and thermal fluxes);
- structural analysis of the propellant grain itself;
- overall performance.

NOTE 2 The ballistic dimensioning of the grain enables the grain geometry to be determined and subsequently to verify conformance to other requirements (e.g. mechanical and fluid dynamics) and the overall performance requirements.

5.6.5.3.6 Ballistics: aspects

a. The pressure and mass flow rate histories and their dispersions shall be known.

b. The pressure and mass flow rate histories shall be calculated taking into account the following:

1. The variation of the combustion surface area.
2. The dependence of the burning rate on the following parameters:
   (a) pressure;
   (b) temperature;
   (c) hump effect;
   (d) erosive burning;
   (e) accelerations (to which the grain is subjected).

c. The burning surface area in relation to burnt depth shall be calculated.

d. The dependence of the burning rate on pressure and temperature, including dispersions, shall be determined in small scale motors.

NOTE The burning rate in a full scale motor is not always the same as in a small scale test motor. The scale factor expresses variations in the burning rate related to the size and configuration of the test motor (small scale) and the scale 1 rocket motor.

5.6.5.3.7 Ballistics: reproducibility

a. If the dispersions in the grain characteristics exceed the specifications, the causes shall be analysed and means to rectify the problem shall be identified.

NOTE 1 Variations in the grain characteristics are caused by:

- variations in ingredients;
- variations in the manufacturing process.

NOTE 2 The problem of grain dispersions is particularly critical for motors operating in pairs (e.g. de-orbiting motors and boosters).

b. To assess the effect of all dispersions, the variations described in a. and in 5.6.5.3.6.d. shall be determined during the development and be combined statistically.

#### 5.6.5.3.8 Ballistics: combustion instability

Combustion instabilities shall be avoided.

NOTE Combustion instability arises because of a coupling between two or more phenomena with the same eigenfrequencies, e.g. the dynamic burning rate of the propellant and the acoustics of the combustion chamber. Combustion instability causes vibrations, severely increased heat transfer and severe loads which can lead to the destruction of the motor.

#### 5.6.5.3.9 Ballistics: oscillatory combustion

Tests with instrumented motors shall assure that any oscillations that occur are in conformance to the motor or system requirements.

NOTE 1 Oscillatory combustion can be caused by the same mechanisms that lead to combustion instability but result in limit cycles (limited amplitudes).

NOTE 2 If there is a long tail-off in the thrust, the motor can operate at very low pressures. In this case another form of oscillatory combustion can occur, $L^*$-oscillations, which can cause severe oscillations to the spacecraft or system.

#### 5.6.5.3.10 Ballistics: acoustics

It shall be ensured that the noise generated by the motor, and the system and subsystem conforms to the system and subsystem requirements.

NOTE The noise generated by a solid motor stems from three sources:

- the noise due to ignition,
- "rough" combustion, that are uncorrelated random pressure oscillations,
- the turbulent interaction of the nozzle exhaust and the atmosphere.

#### 5.6.5.3.11 Mechanical aspects: loads

The grain can be subjected to the following loads:

a. Thermal shrinkage of the propellant after curing. This effect depends on curing pressure and temperature.

b. Internal pressure.

c. Pressure gradients in the combustion chamber.

d. Accelerations due to gravity and launch vehicle operations.

e. Vibrations.

f. Transport, storage and handling.

#### 5.6.5.3.12 Mechanical aspects: dimensioning

For dimensioning, the following applies to the loads considered in 5.6.5.3.11:

a. Thermal shrinkage and internal pressure (see 5.6.5.3.11.a. and 5.6.5.3.11.b.) shall be taken into account.

b. When considering the internal pressure (see 5.6.5.3.11.b.), the mechanical properties of the propellant shall be considered in relation to the rate of change of pressure during ignition (deformation of casing and grain).

c. The pressure gradients in the combustion chamber (see 5.6.5.3.11.c.) shall be taken into account for special grain configurations, for example, slotted grains ignition (deformation of the grain).

d. When considering accelerations due to gravity and launch vehicle operations (see 5.6.5.3.11.d.), creep shall be taken into account.

e. It shall be assumed that different loads can act simultaneously.

f. The different loads may be assumed to be linearly related.

g. The dimensioning shall also take the bonding to the thermal protection into account.

h. Stress concentrations and ageing of material shall be taken into account.

NOTE This is especially important for the strength and modulus of elasticity.

i. The visco-elastic character shall be taken into account.

j. Visco-eleastic and visco-plastic properties of the grain shall be reported according to Annex M.

k. To prevent the grain failure, the equivalent uni-axial load shall be compared to the elongation and stress measured under corresponding equivalent tension, rate of deformation and temperature (master curve).

NOTE A factor of safety, FOS = 1,5 to 2 on ultimate loads is commonly used.

l. The demonstration of the appropriateness of the analysis codes for a., b., g., h. and i. shall be in accordance with Annex N.

### 5.6.5.4 Nozzle assembly

#### 5.6.5.4.1 Overview

Solid rocket motors for launchers usually have a single nozzle, which can be canted for certain applications, with the possibility of thrust deflection by fluid injection or by a flexible bearing.

Solid rocket motors for spacecraft usually have a single nozzle, in some cases with the possibility of thrust deflection.

The nozzle throat area, together with the propellant grain characteristics determines the mass flow rate and the pressure history. Special materials able to withstand the high temperatures and erosion induced by the flow of combustion products are used for the nozzle.

The main requirements and the geometry of the nozzle are determined at the motor level: the pressure level and burning time, the throat diameter and area ratio, and the level of submergence depend on the overall motor design.

The different components of the nozzle are:

- fixed housing;
- flexible bearing (in the case of TVC);
- nozzle thermal protection;
- fluid injection ports (in the case of TVC);
- nozzle housing (structure);
- nozzle closure;
- brackets, reinforcement ring (in the case of TVC).

NOTE Some components can be combined.

#### 5.6.5.4.2 General

A trade-off of nozzle concepts shall be made, taking into account the requirements, performances and costs.

#### 5.6.5.4.3 Main functions and constraints

a. The main functions to be performed by the nozzle are as follows:

1. It shall provide the specified thrust for propulsion and accelerate the flow to generate additional momentum.
2. It shall have TVC capabilities (if specified).
3. It shall withstand the mechanical and thermal loads during the mission and manufacturing.

b. The main constraints to be conformed to by the nozzle are as follows:

1. It shall be compatible with the motor case and thermal insulation in the aft part of the case.
2. It shall be compatible with the grain geometry.
3. It shall be compatible with the combustion products.
4. It shall be compatible with the TVC system.
5. It shall be compatible with the environment.

#### 5.6.5.4.4 Fixed housing (structure): overview

The fixed housing (structure) provides the mounting of the nozzle to the motor case; its geometry depends on the level of submergence.

Depending on the motor case, materials and design, the fixed housing for large boosters is usually made from metal.

For small motors or solid motors for spacecraft, depending on the motor case, materials and design, parts of the nozzle structure are usually made from metal.

#### 5.6.5.4.5 Fixed housing (structure): general

a. For the fixed housing structure, the following loads shall be taken into account:

1. pressure;
2. thrust;
3. TVC reaction forces.

NOTE For the fixed housing or nozzle structure, see ECSS-E-30-01, ECSS-E-30-02A subclauses 4.1 through 4.6, and ECSS-E-30 Part 8A subclauses 4.5 through 4.7.

b. The connection zone of the fixed housing and the case shall be analysed with regard to:

1. leak tightness (no leakage under pressure);
2. deformation under pressure (absolute and with respect to the case and the fixed housing).

#### 5.6.5.4.6 Fixed housing (structure): large boosters

a. The fixed housing for large boosters shall be protected with a thermal insulation (e.g. rubber, carbon-phenol, or silica-phenol).

b. For a submerged and canted nozzle, where an asymmetric vortex can cause locally increased heat transfer, this shall be specifically addressed in the design of the thermal protection.

#### 5.6.5.4.7 Flexible bearing: overview

The flexible bearing consists of a stack of rubber blades with intermediate layers of rigid material (e.g. steel, carbon-epoxy, glass-epoxy). This stack of shims, through interface mountings, connects the fixed housing to the movable section of the nozzle. The flexible bearing is either cylindrical or conical, with the centre of rotation upstream or downstream to the flexible bearing.

5.6.5.4.8 Flexible bearing: general

a. The flexible bearing shall always operate under compression.

b. As the flexible bearing is considered to be a cold part, it shall be protected from the propellant combustion products in order to maintain its integrity and functional characteristics (stiffness, transverse and tilting, and leak tightness).

c. The protection of the flexible bearing shall be designed such that it:

   1. does not impair the nozzle deflection;
   2. functions according to the system requirements during the complete mission;
   3. protects the flexible bearing from the thermal fluxes.

d. The resistance of the protection shall be taken into account in determining the moment to deflect the nozzle.

e. In the sizing of the flexible bearing the following shall be taken into account:

   1. the requirements for the maximum deflection angle;
   2. the available moment to deflect the nozzle, if specified;
   3. the geometrical envelope (throat diameter, thickness of thermal protection).

f. The geometry and layout of the flexible bearing (i.e. radius, thickness of layers, the number of layers, the internal and external diameter) shall be such that they conform to requirements a. to e.

5.6.5.4.9 Flexible bearing: loads

The flexible bearing is subject to the loads resulting from:

- pressure (internal pressure from the motor) and the part of the thrust acting on the nozzle;
- the gimbaling angle;
- the loads exerted by the actuators through the fixed housing and nozzle housing.

5.6.5.4.10 Flexible bearing: failure modes

The failure modes for a flexible nozzle are:

- loss of tightness and integrity;
- performance (moment) that does not conform to the requirements.

5.6.5.4.11 Flexible bearing: safety margins

By limiting the tilting stiffness of the flexible bearing, the sizing shall satisfy the safety margins with regard to the following failure criteria:

a. buckling of the shims (metal shims);

b. over-stress or over-strain of the shims (composite shims);

c. over-strain and over-shear of the elastomer;

d. insufficient shear strength of the bonding of the elastomer to the shim.

5.6.5.4.12 Flexible bearing: deflection of the nozzle

a. In determining the moment to deflect the nozzle, the following effects shall be taken into account:

   1. resistance of flexible bearing;
   2. resistance of the protection of the flexible bearing;
   3. fluid dynamic forces;

4. effects of ageing on the stiffness of polymer materials.

NOTE The resistance against deflection of a flexible bearing usually diminishes with increasing operating pressure; this resistance (stiffness) can practically vanish, which can lead to an unacceptable behaviour.

b. The power and force to be provided by the actuators shall be determined after a study of the complete lifetime of the TVC system has been carried out and be in conformance to the system requirements.

c. A margin (e.g. 10 % of the stiffness at EOL) on the deflection moment shall be taken into account to assure conformance with the TVC requirements at EOL.

#### 5.6.5.4.13 Nozzle thermal protection: overview

The nozzle itself consists of the entrance section, the throat and the expansion section. The structural parts of the nozzle, that are connected to the flexible bearing (in the case of TVC), or the fixed housing or structure and the TVC-jackets (in the case of TVC), have temperature restrictions. To this end, the inside of the nozzle consists of heat and erosion resistive material that also serves to limit the temperature of the structural parts of the nozzle.

The erosion resistive structure and the insulation protection of the nozzle are linked together or to the nozzle structure ensuring the integrity of the nozzle's mechanical components.

The nozzle geometry is determined by a fluid dynamic design observing the composition of the combustion products, taking into account the (sub) system geometrical constraints (e.g. external length, exit diameter, expected throat erosion).

#### 5.6.5.4.14 Nozzle thermal protection: effects on the nozzle materials

For the nozzle, the following effects on the materials shall be taken into account:

a. erosion;

b. thermal loads;

c. mechanical loads.

All these 3 effects have a similar impact on the entrance section.

Erosion has a major effect on the throat region. This is because the throat area is an important parameter in controlling the motor pressure. Selection of the proper material for the nozzle throat is critical.

In the expansion section, the erosion effects for a well-designed contour (avoiding impact of particles) are not severe.

#### 5.6.5.4.15 Nozzle thermal protection: materials

The following types of material can be used for the nozzle components:

- High temperature materials in contact with combustion products (e.g. pyrolytic graphite, carbon-carbon and refractory metals).
- Ablative materials in contact with combustion products (e.g. carbon-phenolic and silica-phenolic).
- Insulating materials used as a sub-layer for insulation purposes (e.g. carbon-phenolic and silica-phenolic).

#### 5.6.5.4.16 Nozzle thermal protection: design, sizing and dimensioning

a. For the design and sizing of the components:

1. the internal profile and flow characteristics established on the basis of performance requirements shall be known;
2. material shall have been selected.

b. For the design the following shall be done:
   1. perform the thermal analysis of the nozzle (components) and subsequent thermo-mechanical dimensioning;
   2. report the thermal analysis in accordance with Annex E.

c. For the thermal dimensioning the following shall be taken into account:
   1. heat load;
   2. thermal characteristics of the material (in relation to material temperatures) including erosion rates, thermal properties and densities;
   3. ablation rates (in relation to the combustion products);
   4. the specified material thickness at the end of the mission;
   5. the interface temperature limits.

d. In determining the dimensions of the components, factors of safety shall be taken into account.

   NOTE For factors of safety, see ECSS E-30 Part 2A subclauses 4.6.14 through 4.6.16.

e. The minimum value for the factor of safety specified in d., shall be 1,1.

f. In dimensioning structurally loaded components, the following shall be taken into account:
   1. The internal temperature distribution of the component during mission life.
   2. Material characteristics in relation to temperature.
   3. Loads, e.g. pressure, shear stress, contact forces, and thermal expansion-contraction.

#### 5.6.5.4.17 Nozzle thermal protection: leak tightness

In areas where gas circulation can lead to failure of (parts of) the nozzle, leak tightness shall be ensured by design or manufacturing processes and control.

#### 5.6.5.4.18 The nozzle housing (structural): overview

The main function of the structural part of the nozzle is to ensure the integrity of (the movable part of) the nozzle during the mission and to transfer the nozzle's contribution to the thrust.

The main loads on the structural part of the nozzle are:

- internal pressure;
- external pressure;
- activation loads (in the case of TVC);
- loads due to mounting of the nozzle.

The stiffness of the nozzle is critical, especially if TVC applies.

#### 5.6.5.4.19 The nozzle housing (structural): concept

a. The structural function of the nozzle may be performed by an insulated structure (cold concept) or by a thermo-structural material (e.g. carbon-carbon) (hot concept).

b. For all cases specified in a., stiffness and strength shall conform to the system and subsystem requirements.

#### 5.6.5.4.20 Nozzle closure

a. If the nozzle is closed by a membrane (metallic or composite material) to protect the propellant from moisture and to enable pressurization of the motor

(usually $N_2$), it shall be ensured that the membrane is leak tight and that the burst pressure does not exceed the specified values.

b. It shall be ensured that on rupturing, the membrane does not damage the nozzle or equipment.

c. For motors operating in space, rupturing of the membrane should not cause debris.

d. If c. is not met, justification shall be provided.

5.6.5.4.21 Actuator attachments

a. The brackets (attachment points) shall have capability for dismounting the actuator for transport, inspection and maintenance.

NOTE In the case of TVC, the structural part of the movable nozzle is attached to actuators that deflect the nozzle and also keep the nozzle in its position.

b. The brackets shall conform to:

1. the local and general stiffness requirements (see 4.3.8.4);
2. the requirements on dynamic loads on the nozzle (see 4.3.3, 4.3.8.5 and 4.3.8.6).

### 5.6.5.5 Igniter

5.6.5.5.1 General

For the pyrotechnic components of the ignition system, refer to ECSS-E-30 Part 6.

An igniter contains one or more initiators.

The initiator ignites a pyrotechnic mixture (pyrotechnic igniter), which in turn, ignites an igniter which resembles a small solid rocket motor (pyrogen igniter). For large solid motors there may be two or more nested pyrogen igniters, the last one being the main igniter that ignites the motor. The pyrotechnic igniter and (nested) pyrogen igniters are called the pyrotechnic or ignition train.

Starting from a system or subsystem command, the ignition system provides the energy needed to start the motor, i.e. to ignite the propellant grain. The initial command is transmitted to the ignition system and amplified by a pyrotechnic device in the form of hot gas or hot particles. The hot material provides the energy to ignite the main igniter or the ignition train.

5.6.5.5.2 Initiators

The number of initiators shall be determined by the reliability requirements.

5.6.5.5.3 Main function

a. The igniter shall produce a flow of hot combustion products able to generate a reliable and reproducible ignition.

NOTE This can be achieved only if the igniter produces a well-defined mass flow rate history, which is distributed over the surface area of the propellant grain to be ignited.

b. A consumable igniter shall withstand all mechanical and thermal loads at least until the moment that full ignition of the motor has been achieved.

c. The igniter shall in no way endanger the functioning of the motor.

d. The igniter shall have the functionality to be dismounted, completely or partly, so that the motor can be transported under national safety regulations.

e. It shall be ensured that the connections between the motor and the igniter, and the connections within the igniter itself, conform to the requirements on motor leak tightness (see 5.6.5.4.17) during the whole mission.

f. The ignition system shall be able to be subjected to tests, independent of the motor.

5.6.5.5.4 Constraints

a. Compatibility

The ignition system shall be compatible with:

1. the command and measurement system;
2. the grain;
3. the motor system.

b. Safety

The ignition system shall conform to the safety requirements (see 4.9.1).

c. Shocks

The shock due to the ignition shall conform to the system and subsystem requirements.

d. Pressure wave

The pressure wave, caused by the motor ignition, shall conform to the system and subsystem requirements.

NOTE The grain configuration affects the pressure wave.

5.6.5.5.5 Material selection

a. It shall be ensured that the selected materials, including those for the igniter grain, conform to the compatibility requirements (see 5.6.5.5.4.a.) during the mission.

b. If one of the materials constituting the ignition system is more sensitive to detonation than the motor propellant, it shall be demonstrated that the design of the ignition system does not create an additional risk due to the introduction of the igniter into the motor with regard to detonation of the motor.

c. The materials shall be selected in conformance to the manufacturing processes, reliability requirements and costs.

d. The selected materials shall conform to the requirements for mission life.

5.6.5.5.6 Ballistics

a. Solid motor requirements shall apply to pyrogen igniters.

b. The design of the case, the thermal protection and the grain shall be in conformance to the general requirements for solid rocket motors (refer to 5.6.5.2, 5.6.5.3, and 5.6.5.4).

NOTE 1 For the igniter, larger safety coefficients than for solid motors are sometimes applied.

NOTE 2 Simplified methods for the design can be applied.

c. The main igniter shall conform to the igniter specification with respect to:

1. propellant mass;
2. operating time;
3. mass flow rate history;
4. temperature and composition of the combustion products.

### 5.6.6 Components: failure modes

Table 2 lists the component failure modes typically encountered in the use of (standard) solid rocket motor components and component assemblies.

### 5.6.7 Thrust vector control (TVC)

For thrust vector control, subclause 4.3.8. applies.

NOTE For solid propulsion systems, the nozzle with the flexible bearing is deflected on command by at least two actuators.

**Table 2: Solid propulsion component failure modes**

| Component type | Failure mode | Failure detection | Failure prevention |
|---|---|---|---|
| Case | Rupture of case | Proof test followed by NDI | Design and quality control |
| | Rupture skirt or case | - | Design and quality control |
| | Leakage | - Pressure test<br>- He leak test | Design and quality control |
| Internal insulation (liner) | Too high an ablation rate | - Post-firing analysis (if possible)<br>- In-flight measurement | Design and quality control |
| | Not inhibiting parts of the grain that should be protected | - NDI<br>- Post-firing analysis (if possible)<br>- In-flight measurement | - Design and quality control<br>- Manufacturing process |
| | Anomalies in opening of stress relief flaps | - Post-firing analysis (if possible)<br>- Accelerometers | - Dimensional control<br>- Quality control<br>- Design |
| | Cracks in insulation (especially where flaps join the remainder of the internal insulation | - NDI<br>- Hot spots | Design and quality or process control |
| | Leakage (composite case) | - Leak test | - Design<br>- Quality control |
| | Ejection of parts of internal insulation | - Post-firing analysis<br>- NDI | - Design<br>- Quality control |
| | Debonds | - NDI<br>- Post-firing analysis | - Design<br>- Quality control |

**Table 2: Solid propulsion component failure modes** *(continued)*

| Component type | Failure mode | Failure detection | Failure prevention |
|---|---|---|---|
| Grain | Erosive burning | Post-firing analysis | Design, propellant formulation |
| | Deviation in pressure or burning rate | Post-firing analysis | - Design, storage (ageing)<br>- Quality control of material and processes<br>- Propellant formulation (sensitiveness to ageing) |
| | Voids, small cracks | NDI | Manufacturing process (mixing, casting) |
| | Combustion instability (oscillatory combustion) | Post-firing analysis | Analysis |
| | Cracks, rupture of grain | NDI | - Quality control<br>- Manufacturing process<br>- Formulation (pot life)<br>- Internal geometry,<br>- Propellant formulation design analysis |
| | Deformation of grain | - NDI,<br>- Post-firing analysis | - Design<br>- Propellant formulation<br>- Structural analysis<br>- Ageing analysis<br>- Design<br>- Proper storage propellant formulation |
| Nozzle | Overheating, resulting in:<br>Rupture of structural parts,<br>Leaks<br>Ejection of parts | Post-firing analysis | - Thermal design<br>- Quality control |
| | Excessive erosion resulting in:<br>- performance loss<br>- non-intentional asymmetric thrust | - Post-firing analysis<br>- Thrust performance analysis | - Thermal design<br>- Quality control |
| | Pocketing | Post-firing analysis | - Structural design<br>- Material selection<br>- Manufacturing process |
| | Loss of integrity | - Post-firing analysis,<br>- Performance loss | - Design<br>- Bonding<br>- Process control<br>- Material selection |
| | Leakage | Leak test | - Seal design<br>- Quality control |
| | Wrong burst pressure of nozzle seal | Post-firing analysis | - Design<br>- Material selection<br>- Manufacturing process |

**Table 2: Solid propulsion component failure modes** *(continued)*

| Component type | Failure mode | Failure detection | Failure prevention |
|---|---|---|---|
| Igniter | Leakage (transducers, seals, initiators) | Leak test | Seal design |
| | No or abnormal ignition behaviour | Pressure measurement | - Redundancy<br>- Design<br>- Quality control |
| | No, or abnormal motor ignition | - Pressure measurement<br>- In-flight measurement | Design,<br>Quality control |
| | Auto ignition or inadvertent ignition of the igniter | Damage assessment | - Safety barriers<br>- Safe and arm device<br>- Electrical continuity design<br>- Avoidance of static electricity<br>- Protection against lightning effects |
| | Too high an ignition peak. | Pressure measurement | - Design<br>- Material selection<br>- Quality control<br>- NDI |
| | Loss of integrity | - Pressure measurement<br>- Post-firing analysis | - Design<br>- Quality control<br>- NDI<br>- Material selection |
| Valves | Undesired operation | - Leak test,<br>- Pressure test | - Cleanliness<br>- Quality control |
| Transducers | Zero shift, measurement anomaly | Calibration | - Incoming inspection<br>- Mounting procedures |
| | Leakage | Leak test | Design, quality control |
| Mechanical connections (including hydraulic and pneumatic connections) | Leakage | - Pressure measurement<br>- Post-firing analysis<br>- In-flight measurement | - Design<br>- Quality assurance<br>- Manufacturing and process control |
| | Rupture | - Burst or proof test followed by NDI<br>- Post-firing analysis | - Design<br>- Quality assurance<br>- Manufacturing and process control<br>- Material selection |
| Electrical connections | No continuity | Resistance measurement | - Design<br>- Quality assurance<br>- Manufacturing and process control |
| | Wrong connections (e.g. interchange of lines) | Measurement of electrical signals | - Design<br>- Quality assurance<br>- Manufacturing and process control |

## 5.7 Ground support equipment (GSE)

### 5.7.1 Safety

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

### 5.7.2 Fluid

a. Relief valves shall be installed on all pressurized vessels and major sections of the lines.

b. The GSE design shall provide evacuation lines to the facility if there is operation of any relief valve.

NOTE See ECSS-E-70.

c. Any contact between materials which, when coming into contact with each other can cause a hazard, shall be avoided by design.

d. The procedures for operation and the design of the equipment:

1. shall be such that inadvertent pressurization of the subsystems is avoided;
2. should avoid all risks.

e. If d.2. is not met, justification shall be provided.

f. The GSE design, functioning and procedures shall ensure that fluids are delivered to the launcher or spacecraft according to their specification (e.g. contamination level, pressure, or temperature).

NOTE Annex A provides examples of specifications with regard to composition and contamination that can be used for this purpose.

g. The GSE shall be designed such that disconnecting lines does not:

1. pose risks, and
2. cause pollution.

### 5.7.3 Electrical

a. Functionality shall be provided for accessing the system to verify the electrical continuity and functionality of all electrically operated equipment.

b. The procedures for operation and the design of the equipment:

1. shall be such that inadvertent activation of the systems and subsystems is avoided,
2. should avoid all risks.

c. If b.2. is not met, justification shall be provided.

d. If the GSE is to be used in the vicinity of inflammable or explosive materials, it shall be explosion proof.

## 5.8 Verification

### 5.8.1 General

For general requirements on the verification of solid propulsion systems for launchers and spacecraft, see subclause 4.6.1.

### 5.8.2 Verification by analysis

For requirements on verification by analysis of solid propulsion systems for launchers and spacecraft, see subclause 4.6.2.

### 5.8.3 Verification by test

#### 5.8.3.1 Overview

In addition to subclause 4.6.3, the requirements specified in subclauses 5.8.3.2 to 5.8.3.4 apply.

The verification by test, according to the compliance matrix, of whether a system, subsystem or component conforms to the requirements, proceeds in three steps:

- Development tests

  During development tests of solid propulsion systems, the system, subsystem, or component is tested within the operational envelope with the following objectives:

  - to verify the functioning of the system, subsystem, or component;
  - to gain confidence in the design and selected materials for undergoing qualification testing;
  - to optimize the design with respect to dimensioning, performance and cost;
  - to verify the suitability of the manufacturing processes and procedures;
  - to verify that the product conforms to the storage and shelf life requirements;
  - to ensure that the motor conforms to the safety requirements of subclause 4.9.

- Ground qualification tests

  The objective of the ground qualification tests is described in 4.6.3.1.h.2.

- Qualification during flight

  The objective of the flight qualification tests is described in 4.6.3.1.h.3.

#### 5.8.3.2 General

a. The following parameters and their evolution during time shall be measured during the ground tests of solid motors:
   1. thrust,
   2. chamber pressure,
   3. igniter pressure.

b. Leak tests shall be performed before ground testing the motor.

c. The mass of the motor shall be determined:
   1. before ground testing, and
   2. after ground testing.

#### 5.8.3.3 Tests on systems, subsystems and components

Table 3 identifies the verification by test that should be performed on components, subsystems and systems of solid propulsion systems.

NOTE Details on the verification of the qualification envelope requirements and acceptance tests are given in subclause 4.6.3.2.

**Table 3: Test on solid propulsion systems, subsystems and components**

| | Item | Verification of requirements for qualification envelope | Acceptance |
|---|---|---|---|
| 1.1 Materials | Metals | - Only characterization for special requirements<br>- New processes | |
| | Fibres | - | |
| | chemicals | - | |
| | pyrotechnic mixtures | Characterization according to approved standards | |
| | (Pre-impregnated) fibre material (e.g. felt, cloth) | Characterization only in special cases. | |

**Table 3: Test on solid propulsion systems, subsystems and components**

| | Item | Verification of requirements for qualification envelope | Acceptance |
|---|---|---|---|
| 1.2 Components | Of the shelf items (standard, non-critical, e.g. bolts, simple instruments, relief valve, O-rings) | - | |
| | Of the shelf items (critical, e.g. pyrotechnic devices, items on the FMECA critical path) | Characterization | |
| | Specially manufactured components | Characterization | |
| | Specially manufactured components: | | |
| | Nozzle flexible bearing | - Dynamic and static characterization test<br>- Ageing behaviour | |
| | Nozzle fixed housing | Characterization under extreme pressure | Proof pressure test $p \geq$ MEOP |
| | Nozzle housing part (structural) | Characterization of stiffness without and with thermal protection | |
| 2. Subsystems | Case | Characterization of:<br>- metal parts: morphological analyses, mechanical characteristics, physical characteristics.<br><br>If there is lack of data or brittle materials: fracture mechanics.<br><br>Corrosion resistance, welding characteristics | Sample testing ($\sigma$, $\varepsilon$) (in the case of heat treatment) |
| | | Complete case: characterization of requirements (e.g. mass, dimensions, leak tightness). | - NDI<br>- Proof pressure test on metallic cases ($p >$ MEOP) |
| | | Characterization of the case under extreme pressure (from the extreme envelope) with (external) loads corresponding to the dimensioning requirements. | |
| | Thermal protection (internal, together with the case) | - Verification of thermal, mechanical, bonding and ablative properties<br>- Effect of ageing on the above characteristics<br>- At motor level: post-firing inspection<br>- In-flight evaluation<br>- Post-flight evaluation | - Verification of leak-tightness when integrated with the case (only if leak-tightness is a requirement for the thermal protection)<br>- Testing of representative bonds (samples) |
| | Thermal protection (external) | - Post-flight evaluation<br>- At motor level: firing test | Verification of bonds (samples) |

**Table 3: Test on solid propulsion systems, subsystems and components**

| | Item | Verification of requirements for qualification envelope | Acceptance |
|---|---|---|---|
| | Grain | - Propellant characterization: ballistic, mechanical, safety, bonding at sample level<br>- Ageing tests<br>- Vibration and thermal cycling tests at loaded case level<br>- NDI on cast grain<br>- Firing test to evaluate the mechanical behaviour of the grain at one or more points of the qualification envelope<br>- Firing test | - Ballistic sample testing for every propellant batch<br>- Bond testing on samples for every propellant batch<br>- Vibration and thermal cycling for small motors as lot acceptance tests (if specified)<br>- NDI on the cast grain |
| | Nozzle and actuation system | - Characterization of mass, dimensions, stiffness, deflection (for movable nozzle), erosion, thermo-mechanical behaviour<br>- Rupture pressure test of nozzle closure disk<br>- Leak tightness<br>- Firing test | - Determination of stiffness<br>- Leak tightness, deflection |
| | Igniter (pyrotechnic) | - Qualification according to ECSS-E-30 Part 6A subclause 4.11.7<br>- Igniter firing tests shall demonstrate its proper functioning, e.g. response times<br>- Safety tests<br>- For redundant ignition chains, demonstration of proper functioning with both chains and a single chain<br>- Motor firing test | - NDI<br>- Lot acceptance tests for series produced igniters |

**Table 3: Test on solid propulsion systems, subsystems and components**

| | Item | Verification of requirements for qualification envelope | Acceptance |
|---|---|---|---|
| | Igniter (pyrogen) | - Qualification according to ECSS-E-30 Part 6A subclause 4.11.7<br>- Characterization under extreme pressure (structural part)<br>- Vibration testing<br>- Verification of the interface with the case<br>- Verification of leak tightness<br>- Firing of the igniter<br>- Safety tests<br>- For redundant ignition chains, demonstration of proper functioning with both chains and a single chain<br>- Motor firing test | - Proof test<br>- NDI<br>- Lot acceptance tests for series produced igniters |
| 3. Systems | Motor | Safety tests | - Dimensions<br>- Mass<br>- Electrical continuity<br>- Leak-tightness |
| | | Ambient tests | TVC test |
| | | Firing tests (with TVC, ground and flight). | For series produced motors, lot acceptance tests |

#### 5.8.3.4 Leak tightness

Specifically for solid propulsion systems, long term storage with a small over pressure shall be evaluated either by pressure measurements during a prolonged period, or by using He and He-detection.

NOTE For leak tightness for small motors see ISO-14304.

### 5.8.4 Verification by inspection

For requirements on verification by inspection of solid propulsion systems for launchers and spacecraft, see subclause 4.6.4.

## 5.9 Production and manufacturing

### 5.9.1 Overview

In addition to this subclause, subclause 4.7 also applies to the production and manufacturing of solid propulsion systems for launchers and spacecraft.

A solid motor is a “one-shot-item” that cannot be submitted to functional acceptance tests.

For the quality of the production and manufacturing methods, see ECSS-Q-20A subclauses 4.7.5 and 4.7.6.

For the structural components of a solid propulsion system or subsystem, see subclause 4.8 of ECSS-E-30 Part 2A.

### 5.9.2 General

a. The loads during manufacturing, handling, test and transport on structural elements, components, subsystems and systems shall be analysed.

b. The manufacturing process, handling and transport shall not contaminate or damage the product.

### 5.9.3 Manufacturing of bonded elements

#### 5.9.3.1 Overview

The thermal protection and some other elements are bonded to other components. Pollution of these elements can seriously deteriorate the polymerization of the thermal protection or the effectiveness of the bonding process and cause debonds or low-quality bonds, see subclauses 5.8.3.3 and 4.6.3.2.

#### 5.9.3.2 Test on bonding samples

Tests on bonding samples should be performed.

#### 5.9.3.3 Manufacturing of the grain

a. The manufacturing of the grain shall take place in a dedicated plant.

b. The plant shall fully conform to the national safety regulations.

NOTE In most countries, national safety regulations specify the dedicated safety analyses for the production, equipment and processes.

c. The quality of the ingredients shall be maintained in conformance to a specification conforming to 4.2.e..

d. It shall be ensured that no degradation of the ingredients take place during storage.

e. The production process of the grain shall:

1. lead to a reproducible product, and
2. be performed by a well-defined, traceable and qualified process.

NOTE The manufacturing process of the grain can strongly affect the ballistic and thermo-mechanical properties of the grain. Therefore, it affects the design and dimensioning of the grain.

f. The manufacturing process shall be taken into account in the design process of the grain.

g. The manufacturing plant shall have provisions to safely handle the waste material.

h. For propellants that are sensitive to humidity, a maximum level for the relative humidity shall be established and observed.

i. The level specified in h. shall not be lower than the minimum level of relative humidity to be maintained for safety reasons.

NOTE Safety regulations specify a minimum level of relative humidity. Some propellants, especially those containing ammonium perchlorate and ammonium nitrate, are hygroscopic.

j. For every grain or lot of grains, ballistic samples shall be tested to verify as a minimum, the burning rate and the mechanical properties (see $4^{th}$ column of Table 3).

NOTE A “lot” of grains is a batch of grains produced from one lot of ingredients in one single production.

k. Bond testing shall take place on samples for every propellant batch (4th column of Table 3).

l. Every grain shall be verified for dimensions, mass and appearance.

NOTE NDI encompasses:

- verification of dimensions,
- mass,
- appearance,
- X-ray and ultra-sound evaluation of the grain structure.

m. X-ray and ultra-sound inspection shall be decided within the program.

n. The grain shall not be considered ready for acceptance unless the following conditions are satisfied:

1. The grain is in conformance to the defined build standard and is identical to the qualified grain.
2. The grain has been manufactured in conformance to the qualified procedures.
3. The measurable properties have been recorded and are within the allowed tolerances.
4. The manufacturing and inspection records are complete and up-to-date with all nonconformances, deviations and waivers cleared.

o. The tooling for the grain shall take the safety requirements into account.

NOTE 1 This especially concerns shocks, friction and electrostatic discharge.

NOTE 2 For additional requirements for tooling, see ECSS-E-30 Part 2A, subclause 4.8.5.

## 5.10 In-service

### 5.10.1 General

In addition to the requirements in this subclause, requirements in 4.8 also apply.

### 5.10.2 Operations

#### 5.10.2.1 General

For operations, subclause 4.8.2 applies in addition to this subclause.

#### 5.10.2.2 In-flight operation

##### 5.10.2.2.1 Control of an upper stage propulsion system during the operation of a lower stage propulsion system

During the operation of a lower stage propulsion system, the propulsion system of the next stage to be activated shall be maintained in the proper condition for ignition, or shall be brought into the proper condition for ignition.

NOTE This includes arming of a pyrotechnic igniter (if present and if arming has not been performed before launch).

##### 5.10.2.2.2 In-flight measurements: overview

A distinction is made between large motors for launchers and spacecraft motors:

- For launcher motors, the objective of in-flight measurements is:
  - to provide information in case of anomalies;
  - to provide information at system level for evaluating the propulsion system performance;

- to provide information for a statistical database.

- For spacecraft motors, a distinction is made between spacecraft motors that are fired shortly after launch (e.g. apogee boost motors) and motors that have a long life in orbit before being fired (e.g. motors for interplanetary flight manoeuvres, de-orbiting motors).

For in-flight measurements, in addition to 4.8.4.2.1, subclauses 5.10.2.2.3 and 5.10.2.2.4 apply.

5.10.2.2.3 In-flight measurements: launcher motors

a. The chamber pressure (in general redundant) should be measured during flight.

b. The propulsion system should be such that the following measurements can be carried out during the flight:

   1. In general:

      (a) pressure in the igniter;

      (b) accelerations and vibrations;

      (c) temperatures at critical positions;

      (d) deformations.

   2. In addition, for TVC with a movable nozzle:

      (a) the nozzle position;

      (b) the force in the nozzle actuation brackets.

c. If b. is not met, justification shall be provided.

5.10.2.2.4 In-flight measurements: spacecraft motors

a. The motor shall be such that the following measurement can be carried out:

   1. chamber pressure;

   2. the outside temperature in critical areas.

b. For motors that have a long life in orbit, the following additional parameters should be measured:

   1. The motor blanket pressure.

      NOTE This is to verify that the motor has not developed leaks.

   2. The motor temperature.

      NOTE This is for an active temperature control system to provide the functionality to limit the temperature and temperature excursions.

# 6

# Liquid propulsion for launchers

## 6.1 General

a. Propulsion systems for liquid propellant launchers shall provide the means, forces and torques to:

1. achieve lift-off,
2. maintain the intended launcher trajectory,
3. separate stages,
4. passivate the spent stage (to avoid creation of debris),
5. ignite any subsequent stage.

b. The last stage, in the case of a GEO mission should provide the means to reach a graveyard orbit.

NOTE 1 For propulsion systems for upper stages, multiple start-stop sequences can also be specified.

NOTE 2 In cryogenic stages, chill-down before ignition is usually also specified.

NOTE 3 In liquid launcher propulsion systems:

- Provisions for TVC are also often specified.
- Usually two types of propellants are used: a fuel and an oxidizer, stored in separate tanks.

NOTE 4 Although the operation time during the flight of a launcher propulsion system is rather short, the development and qualification tests can specify that the engine is able to withstand a substantially longer duration of total firing time and to undergo a number of cycles.

c. If b. is not met, justification shall be provided.

d. The liquid propulsion system shall have capability for easy replacement of parts, components and subsystems.

e. Instrumentation should be such that pre-flight predictions can be verified or the cause of potential (in-flight) failures can be identified.

f. If e. is not met, justification shall be provided.

g. 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 immediately identified.

NOTE This also applies to the propulsion GSE design requirements, defined in ECSS-E-70.

## 6.2 Mission

The liquid propulsion system shall conform to the launcher mission requirements in terms of the following:

a. pre-launch activities (acceptance tests, storage, ageing before use, transport, integration and waiting on the launch pad);

b. launch (including launch-abort activities);

c. flight;

d. in-flight operations;

e. de-orbiting and re-orbiting.

NOTE The propulsion system conforms to the mission requirements by providing a main thrust to provide the $\Delta V$, and by providing attitude control and propellant settling. The main propulsion system can provide all these functions, or an additional propulsion system (RCS) can provide attitude control and propellant settling. Combination of both solutions can also be used.

## 6.3 Functional

a. The propulsion system shall:

1. conform to the interfaces (see 6.5), and
2. provide the specified specific impulse, total impulse (accounting for deviations and item-to-item variations) and thrust (accounting for deviations and item-to-item variations) versus time.

b. The thrust level (profile) shall be defined, taking into account the following launcher system constraints:

1. the general loads on the launcher (due to aerodynamics, thermal heating and guidance);
2. the induced accelerations.

c. The following aspects shall be covered:

1. thrust level versus time;
2. maximum TVC angle;
3. burning time;
4. start-up and shutdown transients;
5. auxiliary power to be delivered to the launcher (e.g. electrical and fluids);
6. residual masses;
7. re-startability, throttling and mixture ratio variation.

d. The transients during start-up and shutdown of the propulsion system shall conform to the launcher requirements and constraints with regard to:

1. lift-off,
2. stage ignition,
3. separation, and
4. mission abort.

e. All external loads, static and dynamic shall be specified and taken into account.

NOTE The dimensioning of external loads are identified in the relevant subclauses on parts, components and subsystems.

f. The propulsion system shall have electrical continuity, including grounding.

g. The propulsion system shall provide TVC or thrust in a fixed direction (with respect to the launcher) according to the system requirements.

NOTE Reliability and safety are functional requirements. For safety, refer to ECSS-Q-40.

## 6.4 Constraints

### 6.4.1 Acceleration

Acceleration levels shall be specified at the propulsion system level.

NOTE The acceleration has an impact on:

- turbo machinery;
- the functioning of the vortex suppression devices in the tank outlets;
- the inlet pressure at the pumps.

### 6.4.2 Geometrical constraints

The dimensioning of the propulsion system and its components shall take into account the overall launcher dimensions, interfaces between stages, ground infrastructure and requirements for transportation.

### 6.4.3 Acoustics and vibrations

Propulsion induced vibrations and acoustic environment shall not exceed the specified limits (amplitude and frequency) of the launcher and the payload.

### 6.4.4 Environmental conditions

The environmental conditions (temperature, humidity, salt content of the atmosphere, aerodynamically induced forces and moments on the propulsion system, and aerodynamically induced heating of the propulsion system) and limitations for the operation of the propulsion system shall be specified.

### 6.4.5 Multiple engines or nozzles on the same stage

a. If a stage has more than one engine (or nozzle), the following shall be taken into account:

1. The interactions between the engines (nozzles): flow interaction and heat fluxes).
2. Accessibility and the interchangeability of systems, subsystems and components.

b. The reporting of the work specified in requested in a.1. shall be in accordance with Annex G.

## 6.5 Interface

The interfaces shall conform to requirements for the whole life of the systems and subsystems, including the following:

a. Other stages of the launcher.

b. Launcher spaceonics.

c. Stage components:

1. skirts;
2. spaceonics (including hardware, OBDH, TM/TC and wiring, tunnels);
3. TVC;
4. stage thermal protection;
5. termination-destruction devices;
6. environmental protection devices (e.g. rain, dust and Sun).

d. Nature of the interfaces, i.e.
   1. geometry, including the analysis of the dimensions for all phases of life (e.g. assembly, transport, flight);
   2. mechanical, including induced loads, static and dynamic;
   3. thermal: thermal fluxes;
   4. electrical, including ensuring electrical continuity;
   5. materials, including ensuring compatibility.

e. Interfaces with GSE and transport, including:
   1. definition of interfaces
      (a) for launcher or spacecraft GSE and transport, and
      (b) with the launch authorities for safety;
   2. the capability for electrically grounding of the systems and subsystems.

## 6.6 Design

### 6.6.1 General

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

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

### 6.6.2 Propulsion system selection and design process

#### 6.6.2.1 System selection

a. The selection of a launcher propulsion system shall:
   1. conform to the launcher system requirements in terms of performance (i.e. thrust, specific impulse, masses, and burn time);
   2. take into account the following:
      — the availability of materials and propellants,
      — the industrial capabilities,
      — the level and availability of technology, and
      — the costs and economics.

b. The selection of the propulsion system shall be based on a trade-off of between the following:
   - the propellant combination,
   - the engine architecture and the propellant storage,
   - pressurization and feed system.

#### 6.6.2.2 Propellant selection

##### 6.6.2.2.1 Overview

There are two basic types of launcher propellants:

- Cryogenic propellants

  Cryogenic propellants are only liquid at extremely low temperatures.

  Cryogenic propellants are, for example, $LH_2$, $LO_2$, and $LCH_4$. The combination of a cryogenic liquid fuel and a cryogenic oxidizer provides the highest specific impulses of all chemical rocket propellants.

- Storable propellants

  Storable propellants are liquid at ambient pressures and small over pressures and ambient temperatures and can be stored for long periods without stringent requirements on temperature control.

  Storable propellants are divided into two groups:

  - Hypergolic combinations, where oxidizer and fuel spontaneously ignite when being brought into contact with each other (examples are $N_2O_4$, RFNA and $HNO_3$ as oxidizers and $N_2H_4$, MMH, and UDMH as fuels).
  - Those that use an ignition system: non-hypergolic propellants include most cryogenic combinations and hydrocarbons and alcohols in combination with a cryogenic oxidizer or a storable oxidizer.

    NOTE Monopropellants such as $N_2H_4$ and $H_2O_2$ are not commonly used for launcher propulsion because of their low performance. They can be used on launchers for the ACS.

##### 6.6.2.2.2 Normative provisions

a. When selecting a propellant (combination) the following aspects shall be taken into account:
   1. conformance to the specific system requirements;
   2. performance;
   3. availability;
   4. handling;
   5. safety;
   6. cost;
   7. impact on the environment.

b. When using the propellants, the respective standards shall be applied.

   NOTE A.2 includes a list of standards that can be used for this purpose.

c. The effect of b. shall be taken into account when selecting the propellant (combination).

#### 6.6.2.3 Propellant storage

##### 6.6.2.3.1 Tank selection

a. The propellant tanks shall conform to the system requirements, including:
   1. the geometry;
   2. the structural function (e.g. loads due to propellant mass, pressure, and external and interface loads) and the requirements due to transfer of forces and torques (static and dynamic);
   3. the mass budget;
   4. the thermal fluxes into the tank.

b. With regard to specific propulsion functions, the tank shall have capability to:
   1. contain the propellant mass within the specified range of pressures and temperatures;
   2. contain devices that limit fluid motions, if these motions, in the absence of these devices, exceed specified limits, with respect to their effects on the feed system and the launcher;
   3. provide the specified mass flow rates to the engines under all specified operational conditions.

c. The selected materials shall be compatible with all the fluids coming into contact with them, and with the specified temperature range.

d. The tank shall conform to the interface requirements (refer to 6.5).

NOTE For details on tank requirements, see 6.6.6.

6.6.2.3.2 Engine feed system

a. The feed system shall deliver the propellants to the engine inlets in their specified pressure and temperature range.

b. The feed system shall be designed to ensure that the mass flow rates and mixture ratio at the engine inlets conform to the specified values.

c. The feed system shall include the damping devices capable of suppressing the expected feed system instabilities (POGO, and fluid dynamic instabilities).

d. The feed system shall be such that the engine can be gimbaled.

e. The feed system shall be such that filling, draining and priming can be performed.

f. The feed system shall be able to provide the specified isolation of the engines from the propellant tanks.

6.6.2.3.3 Pressurization system selection

a. The pressurization system shall be selected in conformance to the system and stage requirements.

b. The selection of the pressurization system shall take into account:
   1. mass budgets,
   2. performance,
   3. compatibility of the pressurant gases with the propellants and materials,
   4. reliability,
   5. safety,
   6. pressure level,
   7. costs,
   8. condensation-evaporation,
   9. temperature ranges.

c. The selection of the pressurization system shall be based on a trade-off between the various pressurization systems:
   1. those using inert gas stored in pressure vessels;
   2. those using internal heater-evaporation systems;
   3. those using combustion gases, either from a separate gas generator, or tapped-off from the rocket engines;
   4. those using part of the engine coolant gas or using an engine heat exchanger;
   5. those introducing hypergolic fuel and oxidizer drops into the oxidizer and fuel tanks, respectively;

6. a combinations of the system 1. to 5.

d. The effect of the pressurization system on the tank structure and components shall be taken into account.

e. The analysis of the pressurization loop shall account for (external) heat fluxes, dynamic behaviour ($\Delta p$, $\Delta T$, coupling between gas-source and propellant tank) and demonstrate conformity to the system requirements.

f. For the purpose of identifying failure modes and effect, a FMECA shall be carried out.

NOTE For FMECA, see ECSS-Q-30-02.

#### 6.6.2.4 Engine

a. The engine shall provide the thrust, specific impulse, and service life according to the system and subsystem requirements.

b. The design shall be based on a trade-off between:

1. engine cycles,
2. architecture and overall dimensions,
3. mass of the engine,
4. engine performance,
5. cost of the engine.

NOTE Requirements on the engine, see subclause 6.6.8.

#### 6.6.2.5 Engine cycle selection

##### 6.6.2.5.1 Overview

A distinction can be made between open cycles (gas-generator, tap-off and bleed cycles) and closed cycles (expander, stage combustion, and pressure-fed cycles).

The open cycle expels part of the mass flow rate at a low specific impulse. The closed cycle expels all the mass flow rate at a high specific impulse. For this reason, a closed cycle for the same chamber pressure, propellant combination and expansion ratio has the highest efficiency.

##### 6.6.2.5.2 Normative provisions

a. When selecting an engine cycle the following shall be taken into account:

1. The pressure-fed cycle.

NOTE The pressure-fed cycle is limited to low pressures and relatively low performance, associated with a very simple engine. As it is necessary to store the propellant at elevated pressures, tank technology to a large extent affects the effectiveness of a pressure-fed propulsion system.

2. The expander cycle.

NOTE The expander cycle is limited to relatively low to medium thrust and chamber pressure due to limitations in heat transfer. The turbines are driven by low temperature (usually fuel) gases with a small pressure drop over the turbine.

3. The bleed cycle.

NOTE The bleed cycle uses a small part of the fuel mass flow rate to cool the engine and drive the turbine after which the turbine exhaust gases are dumped over board. The turbines operate on medium temperature (fuel) gases with a large pressure drop over the turbine.

4. The gas generator cycle.

   NOTE The gas generator cycle has a gas generator operating at medium pressure, the turbines are driven by high temperature combustion gases with a large pressure drop over the turbine. The turbine exhaust gases are dumped over board or re-injected, downstream in the nozzle.

5. The tap-off cycle.

   NOTE The tap-off cycle uses a small mass flow rate, directly from the main combustion chamber to drive the turbines. The turbines are driven by medium to high temperature gases with a large pressure drop over the turbine. The turbine exhaust gases are dumped over board, or re-injected into the nozzle extension.

6. The staged combustion cycle.

   NOTE The staged combustion cycle has one or more pre-combustion chambers operating at very high pressures. Part or all (full flow staged combustion cycle) of the propellants are fed into the pre-combustion chamber or chambers and afterwards drive the turbine. The turbine is driven by high temperature, high pressure combustion gases with a small pressure drop over the turbine. The turbine exhaust gases are fed into the main chamber.

b. The cycle shall be selected in conformance to the system requirements, taking into account:

   1. global stage performance,
   2. complexity,
   3. costs,
   4. industrial infra structure,
   5. reliability.

#### 6.6.2.6 Selection of the TVC system

a. A TVC system shall be selected that conforms to the system requirements and be based on a trade-off between

   - gimbaling,
   - differential throttling,
   - fluid injection,
   - vernier engines,
   - flaps or vanes, or
   - any combination of these,

b. The trade-off specified in a. shall take into account:

   1. the global mass,
   2. the complexity,
   3. the losses or gains in specific impulse,
   4. the costs,
   5. the reliability,
   6. the layout.

### 6.6.3 Development

#### 6.6.3.1 General

As liquid propulsion systems for launchers are large, complex, and comprise many subsystems, the development process shall be:

a. structured,

b. well-defined,

c. justified, and

d. strictly controlled.

NOTE The objective of the development process is to arrive at a well-defined and reproducible liquid propulsion system.

#### 6.6.3.2 Development phases

##### 6.6.3.2.1 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 of
  - components, and
  - subsystems;
- integration of subsystem and system;
- testing of:
  - components,
  - subsystems,
  - engines, and
  - system (functional stage);
- problem solving;
- freezing of the design.

##### 6.6.3.2.2 Normative provisions

a. A development plan shall be established taking into account the phases described in 6.6.3.2.1.

NOTE The objective is to arrive at a design that can be qualified against the requirements (see 6.8). The development is completed once the product has been qualified according to the verification requirements (see 6.8).

b. The risk analysis of the preliminary design and trade-off of various options described in 6.6.3.2.1 shall include a FMECA.

NOTE For FMECA, see ECSS-Q-30-02.

c. All unacceptable failure modes from the FMECA described in b. shall be avoided by design.

#### 6.6.3.3 Development logic

a. During the development the following shall be established:

1. all characteristics of the system, subsystems and components;
2. the manufacturing and control processes.

NOTE The objective is to arrive at a product satisfying the maximum product-to-product variation limit, while conforming to the functional, performance and system requirements (see g.).

b. To establish and freeze the design:

1. the sizing process shall be executed;
2. verification models shall be established;
3. validation and verification tests shall be executed.

c. The testing, analyses and experience should identify all possible failure modes.

d. If c. is not carried out, justification shall be provided.

e. The characteristics of the system, subsystems and components shall be established from analyses, characterization of materials, test results and correlation with models.

f. The critical technologies, manufacturing and control processes shall be established, described and justified.

g. It shall be demonstrated that the manufacturing and control processes lead to products that satisfy the maximum product-to-product variation limit while conforming to the system requirements.

NOTE For complex systems, conformity to this requirement can be demonstrated only after a large number of units are produced.

h. System verification shall be obtained by testing a representative propulsion system: this is the only method for obtaining verification of the system.

i. Where knowledge of margins cannot be obtained by analyses and standard tests, materials, components and subsystems shall undergo limit testing.

j. The completely integrated system, including the electrical system shall be tested.

### 6.6.4 Design at propulsion level

#### 6.6.4.1 Contamination

##### 6.6.4.1.1 Overview

The most common types of contamination encountered in launcher liquid propulsion systems are:

- particulate;
- non volatile residue (NVR);
- chemical (e.g. acidity, alkalinity);
- biological;
- moisture.

6.6.4.1.2 General

a. For cryogenic propulsion systems, it shall be ensured that moisture contamination does not lead to icing.

b. Both design-inherent and occasional contamination shall be taken into account, the latter being identified through a comprehensive FMECA.

c. Contamination levels shall be expressed according to standards conforming to 4.2.e.

NOTE MIL-STD-1246C and NAS 1638 are example of standards that can be used for this purpose.

d. Sources of contamination shall be identified and contamination shall be controlled during the manufacture, assembly, and the mission.

e. Appropriate cleaning, drying and control processes shall be implemented and qualified in accordance with standards conforming to 4.2.e.

NOTE These requirements are important for non-regular operations (e.g. launch-abort, replacement of components on the launch platform).

6.6.4.1.3 External contamination

The propulsion system shall be protected to the specified level against the intrusion of external contaminants (e.g. dust, particles, moisture, oil and insects).

6.6.4.1.4 Internal contamination

a. The cleanliness level of the supplied propellants and fluids shall be specified and controlled, both for on-ground and flight operation.

NOTE The presence of contaminants (including propellant vapours) inside the propulsion system can lead to the loss of performance of some components or even to catastrophic failures.

b. Based on the fluid flow synopsis, a contamination tree of the propulsion system shall be established, taking into consideration for each subsystem or component:

1. the inlet contamination,
2. the pre-existing and the generated internal contamination,
3. the resulting outlet contamination.

c. The maximum limit for the level of contaminants inside each component of the propulsion system shall be:

1. identified and specified;
2. compared with the maximum level of contaminants expected from the contamination tree analysis specified in b.

d. If the comparison specified in c.2. shows a nonconformance, the design of the propulsion system shall be upgraded (e.g. by introduction of filters) until full conformance is reached.

e. Procedures shall be established and qualified to ensure that replacing components or subsystems does not introduce internal contamination.

#### 6.6.4.2 Leakage and risks

##### 6.6.4.2.1 Risks of accidental fire or explosion

a. The propulsion system design shall prevent propellant explosions or leakage risks.

NOTE Some materials (e.g. titanium, magnesium) react violently when put into contact with some propellants or fluids (e.g. LOx, NTO, CFC).

b. The verification of a. shall be supported by review of the design and by simulation and testing.

c. The propulsion system requirements shall prevent undesired mixtures, migration or leakage of propellant, and propellant vapours during the whole mission.

d. The propulsion system requirements shall specify operation under conditions different from flight conditions (e.g. ground tests).

e. The choice of materials shall be compatible with the selected propellants and fluids in view of the mission requirements.

f. The choice of service fluids and solvents shall be compatible with the selected materials.

g. If unacceptable risks are identified in requirements a. to e., measures shall be implemented to reduce the risks to acceptable levels and a risk analysis shall be carried out, including the risk of accidental fire explosion.

NOTE For risk management, see ECSS-M-00-03.

h. For monopropellants that develop vapour, the following conditions, which can cause decomposition of the vapour, shall be prevented:

1. rapid compression,
2. contact with hot spots and catalyst materials.

i. Dissimilar propellant lines shall not be located in contact with each other.

NOTE It is good design practice to locate them as far away as possible from each other.

j. If $O_2$ and $H_2$ lines are used in the vicinity of each other, the $H_2$ line should be located above the $O_2$ line to reduce the risk of mixing of the $H_2$ and $O_2$ in case of leaks.

##### 6.6.4.2.2 External leakage

a. If the risk analysis shows unacceptable hazards due to the amount of leakage, measures shall be taken to remove, dilute or collect any fluid that can leak into closed areas (e.g. ventilation, controlled burning of propellant that leaks from the propulsion system or motor, collection of leaked fluids).

NOTE Propellant and fluid leaks into closed areas, such as, test cells and thrust bays, can lead to dangerous situations (e.g. toxicity, risks of fire and explosion).

b. Leaks shall be identified and the volume of leakage shall be quantified.

c. The nominal leaks from the motor or the propulsion system shall be identified and quantified.

NOTE This enables appropriate measures to be taken to remove or dilute the propellant from closed areas.

d. The concentration of hydrogen and oxygen around a test specimen shall be measured and action shall be taken to avoid hazardous situations.

NOTE Hydrogen forms explosive mixtures with air for a wide range of mixture ratio's; and pure oxygen, in combination with organic materials, such as, grease, oil or cloth can lead to serious fires.

e. The design and the assembly of joints and seals shall take into account the sensitivity for leakage.

NOTE Joints and static seals are locations where leakage can be expected.

f. The design and manufacturing of joints and seals shall conform to the requirements following from the leakage budget

NOTE See subclause 6.6.4.2.4.

g. Assembly procedures conforming to 4.2.e. shall be implemented for leak sensitive seals and joints.

h. During the development, it shall be verified that the seals and joints conform to the propulsion system requirements during the whole operational phase including transients.

#### 6.6.4.2.3 Internal leakage

a. Unwanted propellant migration shall be prevented by design (e.g. by a sufficient number of check valves or minimization of pressure differences).

NOTE Due to internal leakage, propellants may migrate within the pressurization lines or feed lines and accumulate in closed areas. When starting the engine this can lead to an undesired contact between dissimilar propellants that can cause fire or explosion.

The contact of dissimilar propellants (especially if $N_2O_4$ is involved) can lead to the formation of nitrates. These nitrates can explode.

In combination with hydrazine (derivatives) sticky compounds can also be formed that can cause valve failures.

b. Migration of the fuel shall be prevented by design or by introducing special measures such as venting or blanketing with inert gas.

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

#### 6.6.4.2.4 Leakage budget

a. An analysis shall be made of the amount of leakage that can be expected for each of the fluids in the propulsion system (leakage budget).

b. It shall be verified that the amount of leakage conforms to the propulsion system requirements.

c. If fluids are used to dilute, ventilate or purge areas where hazardous concentrations of fluids can be expected due to leakage, the amount of these fluids shall be accounted for in the leakage budget.

#### 6.6.4.3 Imbalance

##### 6.6.4.3.1 General

In addition to subclause 4.3.7, for liquid propulsion systems, this subclause 6.6.4.3 also applies.

##### 6.6.4.3.2 Mass imbalance

If it is expected that during the mission the mass imbalance may exceed the specified limits, one of the following shall be performed:

a. Design changes shall be introduced that ensure that the mass imbalance conforms to the specified limits.

b. An active control system shall be implemented to keep the mass imbalance within the specified limits.

##### 6.6.4.3.3 Pressure imbalance

If it is expected that during the mission the pressure imbalance may exceed the specified limits, either

- design changes shall be introduced that ensure that the pressure imbalance conforms to the specified limits, or
- an active control system shall be implemented to keep the pressure imbalance within the specified limits.

NOTE Pressure imbalance affects the engine due to the flexible connection between the engine and the stage and the difference in the pump inlet pressures for the fuel and the oxidizer.

#### 6.6.4.4 System filling and draining

##### 6.6.4.4.1 System filling

a. The filling of the propulsion system shall use valves and lines that
   1. provide an interface with the GSE, and
   2. enable the propulsion system to be filled with fluids.

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

c. The filling subsystem may be combined with the draining functions.

##### 6.6.4.4.2 Draining on ground

a. The draining on the ground subsystem of the propulsion subsystem shall use valves and lines that
   1. provide an interface with the GSE,
   2. enable fluids to be drained from the propulsion system, and
   3. collect the fluids that are removed from the propulsion system.

b. The draining subsystem shall be in conformance to ISO 15389:2001(E) subclauses 4.4 to 4.7, and subclauses 4.9 and 4.20.

c. The draining subsystem may be combined with the filling subsystem.

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

   EXAMPLE Draining through the purging circuit.

6.6.4.4.3 Draining in flight

a. The flow-paths for in-flight draining shall be identified according to the system requirements.

NOTE 1 In-flight draining is specified in some cases of stage passivation.

NOTE 2 In-flight draining can take place along different flow paths than on-ground draining.

b. In-flight draining shall not create hazardous conditions for the stage (e.g. the generation of debris).

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

6.6.4.4.4 Flushing, purging and venting

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

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

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

d. Hazards to personnel, the environment and the system shall be avoided by the design of the flushing and purging systems.

e. Measures shall be taken to ensure that vented fluids do not create hazardous situations (e.g. burn-off of vented hydrogen).

f. Venting in flight shall not create unwanted propulsive effects (e.g. non-propulsive venting).

#### 6.6.4.5 Blow-down ratio

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

NOTE During expulsion of the propellant, the tank pressure, and hence the engine operating pressure, decreases. If blow-down propulsion systems are used on launchers, this is usually the case for (small) auxiliary engines, e.g. for attitude control.

### 6.6.5 Pressure vessels, pressure components and pressurized hardware

a. In the design of pressure vessels, pressure components and pressurized hardware:

1. The factors of safety (FOS) and margins (on MEOP) shall be applied for proof testing and subsequent component life.

   NOTE See also 4.3.5.

2. Environmental aspects shall be taken into account, including:

   (a) temperature,

   (b) vibration levels,

   (c) humidity,

   (d) corrosive environment,

   (e) vacuum.

b. It shall be verified that all pressurized components and hardware can withstand the combined pressure, thermal and dynamic loads as defined by the extreme envelope.

c. A load case analysis shall be made to establish the combined loads on components and hardware during their operational life, to avoid over-specification of the load cases on components and hardware.

NOTE See also 4.9.

d. All pressurized connections and interfaces shall be designed such that they remain leak tight during any of the load cases identified in the load case analysis.

### 6.6.6 Propellant tanks and management

#### 6.6.6.1 General

a. The reporting shall be in accordance with Annex D.

b. The tank design shall take into account the mission profile.

NOTE The design of the tank is influenced by whether there is a single burn of the propulsion system or multiple burns. For example, with the use of baffles, anti-sloshing devices, and the requirement for using a propellant management device.

c. To determine the tank volume, the following shall be taken into account:

1. The amount of propellant to be used during nominal propulsion operations.

NOTE This is derived from the stage requirements and the mixture ratio.

2. The amount of propellant reserves that are derived from the deviations in the engine settings and deviations in the launcher performance (e.g. deviation in drag).
3. Losses and ejected propellants (e.g. boil-off for cryogenic propellants, and venting propellant gases used for attitude control).
4. The amount of unusable propellant (for cryogenic propellants due to temperature variations in the propellant, for storable propellants due to the expulsion efficiency being smaller than unity).
5. The amount of propellant used for chill-down, in the case of cryogenic propellants.
6. The amount of unusable propellant left in the feed lines.
7. The amount of propellant used during start-up and shutdown.
8. The ullage volume that derived in subclause 6.6.6.2.

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

e. The volumes of equipment and lines within the tank shall be taken into account when determining the useful tank volume.

f. If present, the internal thermal insulation of the tank shall be taken into account when determining the useful tank volume.

g. The ullage volume shall be large enough to ensure that:

1. the pressurization system operates as specified;
2. no propellant enters the pressurization system;
3. pressure excursions during the pressurization or the first part of the flight remain within their specified values.

NOTE For PED and STD tanks refer to 5.5.16 in ECSS-E-30 Part 5.1.

h. The tank shall be such that an accurate measurement of the loaded propellant can be made.

i. The systems to accomplish g. shall be taken into account early in the design phase (project Phases A and B).

#### 6.6.6.2 Tank pressure

##### 6.6.6.2.1 General

a. The following shall be taken into account in the tank design:

1. empty, pressurised tanks, can undergo pressure changes due to transport from a hot (climatic) environment to a cool environment and vice versa;
2. uneven cooling or heating can cause pressure differences which introduce severe loads.

b. During engine operation, the engine inlet pressure shall lie within the specified range.

c. The propellant feed system shall ensure that the range in the inlet pressure is maintained during all operational conditions.

NOTE The engine inlet pressure is derived from:

$$p_{ei}(T) = P_{ul}(T) + \rho_p(T)\underline{a}\,\underline{H}(T) + \tfrac{1}{2}\rho_p(T)V^2 + \Sigma\Delta p_{pump} - \Sigma\Delta p_L$$

where:

- $\rho_p$(T) is the propellant density, which is temperature dependant;
- $\underline{a}$ is the (vectorial) acceleration;
- $\underline{H}(T)$ is the (vectorial) height of the propellant above the engine inlet valve;
- $\Sigma\Delta p_L$ is the total amount of pressure losses in the feed system;
- $\Sigma\Delta p_{pump}$ is the pressure rise provided by a possible (boost) pump in front of the engine valve.

The dynamic term, $^1/_2\,\rho_p(T)V^2$ is usually small, but not negligible.

d. The ullage pressure, $p_{ul}(T)$, shall be such that the engine inlet pressure, $p_{ei}(T)$, always conforms to the specified range for all specified operational conditions.

##### 6.6.6.2.2 Maximum tank pressure

a. In determining the tank MEOP, the hysteresis of pressure regulators and uncertainties (e.g. acceleration, temperature, propellant properties and inaccuracies), shall be accounted for.

NOTE The maximum pressure in the tank is derived from:

$$p_{\max}(T) = P_{ul}(T^*) + \rho_p(T^*)\underline{a}\,\underline{H}(T^*)$$

where:

$T^*$ is the temperature that leads to the maximum pressure.

b. After the MEOP has been determined and subsequently specified, it shall be ensured that the ullage volume is large enough to ensure that thermal expansion does not lead to pressures exceeding the MEOP.

6.6.6.2.3 Minimum tank pressure

a. At all times it shall be ensured that during the operational life, the tank pressure is never below the specified minimum tank pressure.

b. The minimum ullage pressure shall be such that the engine inlet pressure is satisfied during all specified operational conditions.

c. In determining the minimum ullage pressure, the hysteresis of pressure regulators and uncertainties (e.g. acceleration, temperature, propellant properties and inaccuracies), shall be taken into account.

d. For turbo pump-fed engines it shall be ensured that:

1. the specified minimum inlet pressure is met or exceeded;
2. the $NPSP_{req}$ is met or exceeded.

NOTE For $NPSP_{req}$ see 3.1.42.

#### 6.6.6.3 Tank draining and emptying

a. The functionality to drain cryogenic tanks during operation shall be provided.

b. There shall be an emergency procedure in case the nominal draining operation fails.

c. For all tanks, the location of fill-and-drain valves and the piping layout, should 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.

d. If c. is not met, justification shall be provided.

e. The tank outlet shall be designed such that under all operational conditions, the specified propellant mass flow rate under the specified thermodynamic conditions is delivered to the engines.

f. Either, the tank design shall be such that when the tank is nearly empty, the occurrence of a vortex is prevented, or an anti-vortex device shall be installed at the sump to avoid gas injection into the feed lines.

g. It shall be ensured that all specified operational conditions, the specified mass flow rate is supplied to the engine inlets.

NOTE Conformance to this requirement can lead to the use of a propellant management device (PMD).

h. A PMD shall conform to the requirements of subclause 5.5.16.4 of ECSS-E-30 Part 5.1A.

i. The tanks shall be loaded and depleted in such a way as to ensure a fuel rich mixture in the rocket engine by loading an excess of fuel in the fuel tank so that that the probability of depleting the oxidizer tank before the fuel tank is 90 % or more.

j. For cryogenic, turbo-pump fed engines, sensors shall be installed in the propellant tanks that enable the propellant level to be measured such that engine operation can be arrested before propellants with a temperature that is too high to ensure that the $NPSP_{cr}$ is exceeded, enters the engines.

#### 6.6.6.4 Anti-sloshing

It shall be ensured that by design, or by installing anti-sloshing devices the following effects do not take place during stage or launcher operation:

a. dynamic coupling between the propellant movement and the stage or a subsequent stage, affecting attitude control and introducing additional loads, even during ground operations;

b. coupling with the pressurization system, either leading to an excessive propellant evaporation, or gas condensation and dissolution;

c. de-stratification, i.e. the minimum propellant temperature towards the end of the stage operation can increase, reducing the amount of usable (cryogenic) propellant;

d. gas ingestion into the propellant feed lines towards the end of stage operation;

e. propellant entering the tank pressurization lines.

#### 6.6.6.5 Common bulkheads

In cases that common bulkheads are used, the following apply:

a. For non-structural (not re-enforced) bulkheads, the pressure on the concave side, shall, during the complete mission, exceed the pressure on the convex side.

b. If cryogenic propellants are used, thermal insulation shall be installed that is sufficient to limit the heat transfer through the common bulkhead to a specified value.

c. It shall be ensured that the heat transfer does not lead to adverse effects (unacceptable cooling or heating of propellants).

#### 6.6.6.6 Temperature management

a. The thermal insulation of the tank shall ensure the following:

1. The temperature of the useful propellant remains within the specified limits for the whole mission.
2. Stratification (cryogenic propellants) is within the specified limits (i.e. limiting the amount of non-useful propellants).

NOTE 1 This is based on the Δmass of insulation material, the –Δmass of the non-useful propellant and the –Δmass of the pressurant gases).

NOTE 2 The main sources for heat transfer are:

- ambient (atmosphere, solar radiation, aerodynamic),
- engines,
- tanks with propellants at different temperatures,
- pressurant gas (cooling can result from the expansion of pressurant gas (blow-down systems) during motor operation).

b. For tanks that function in a ballistic phase, a detailed thermal balance (solar radiation, radiation from the stage to the environment, and internal heat fluxes within the stage) shall be made.

c. In the tank design, the effect of the tank layout and architecture on the temperature management shall be taken into account for tanks that function in a ballistic phase.

#### 6.6.6.7 Fluid dynamic forces on devices

a. If anti-sloshing, anti-vortex, or other devices that interfere with fluid dynamic motions are installed, the fluid dynamic forces shall be

1. analysed, including virtual fluid masses,
2. taken into account in the mechanical design, and

b. The analysis specified in a.1. shall be in accordance with Annex H.

#### 6.6.6.8 Materials

a. Materials shall be selected in accordance with the envisaged propellants and maximum storage time of the propellants in the tanks, temperatures and the environment for the complete mission.

b. In selecting the materials, the following shall be taken into account:

1. Mechanical properties of the materials can change substantially between operating temperature and room temperature.

   NOTE Material temperatures are not always homogeneous.

2. Some materials are susceptible to interaction with propellants (e.g. hydrogen embrittlement, oxygen incompatibility, $N_2O_4$ incompatibility, and $N_2H_4$ decomposition).

#### 6.6.6.9 Tank pressurization

##### 6.6.6.9.1 Overview

The variables that determine the design of the pressurization system are:

- the gas injection temperature,
- the propellant mass flow rate, and
- the range of specified tank pressures.

The amount of pressurant used to pressurize the propellant tank, solely depends on the initial and final state of the propellant tank and possible storage tanks (pressure, volume and temperature), and a margin in case the pressurization system contains pressure regulators (hysteresis).

##### 6.6.6.9.2 General

a. To determine the final state of the pressurant tank, the worst case shall be considered:

   1. minimum temperature,
   2. maximum final volume,
   3. maximum pressure, and
   4. maximum venting of pressurant gases.

b. If a gas storage system is used, the dimensioning shall be based on minimum temperature and maximum final pressure (based on pressure regulator characteristics, if present).

c. Leakage of pressurant gases through equipment in the pressurization system shall be taken into account.

d. For the initial design a 30 % margin shall be taken.

e. It shall be ensured that:

   1. the pressurization system does not induce pressure oscillations in the propulsion system or stage;
   2. there is no back flow into the pressurization system.

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

##### 6.6.6.9.3 Heat exchanger-evaporator

a. If originally cold fluids are used for tank pressurization it shall be taken into account that this can lead to the implementation of a heat exchanger to heat the fluids.

b. It shall be ensured that the capacity of the heat exchanger conforms to the propulsion system requirements during the whole mission.

c. If the engine is used as a heat exchanger, the design shall take into account the interface of the pressurization system with the engine system.

d. A FMECA of the pressurization system shall be carried out.

   NOTE For FMECA, see ECSS-Q-30-02.

## 6.6.7 Propellant feed system

### 6.6.7.1 General

#### 6.6.7.1.1 Overview

The propellant feed system consists of the pipes and lines, with all the associated equipment (e.g. valves and POGO control devices) between the tank outlet (after a sump or anti-vortex device) and the engine inlets.

The function of the propellant 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).

#### 6.6.7.1.2 Normative provisions

a. The feed system should ensure a homogeneous parallel flow at the engine inlet.

b. If a. is not met, justification shall be provided.

### 6.6.7.2 Pressure drop

a. The pressure drops in the feed system shall be determined by calculations or tests, taking into account the characteristics of the components constituting the feed system.

b. The deviations in the various contributions should be accounted for statistically.

c. If b. is not met, justification shall be provided.

### 6.6.7.3 Dynamic effects

#### 6.6.7.3.1 Non-stationary effects

The occurrence of pressure fluctuations shall be analysed and the system shall be designed so that no adverse effects 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.

#### 6.6.7.3.2 Water-hammer effect

a. The water-hammer effect shall be avoided by either using valves with a sufficiently long opening–closing time, or by introducing damping devices in the feed system.

NOTE The water-hammer effect is related to a shock-like change in the mass flow rate, caused by the rapid closing or opening of a valve (on-board or on-ground) or the rupture of a membrane. It is accompanied by very high and shock-like pressure increases.

b. The water-hammer effect phenomenon shall be analysed.

c. It shall be ensured that no water-hammer phenomena occur during the mission.

#### 6.6.7.3.3 Propulsion system dynamic interaction with vehicle structure (POGO)

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

NOTE POGO is a coupling between the dynamic behaviour of the launcher structure and a fluctuating thrust, resulting in a fluctuation of the mass flow rate at the engine inlet. If necessary, the easiest way to suppress POGO is by introducing an anti-POGO device in order to suppress the fluctuations in the mass flow rate.

b. If an anti-POGO device is used, it should be located at the position in the feed system where the maximum amplitudes in the pressure fluctuations occur.

c. If b. is not met, justification shall be provided.

d. The risk of the occurrence of POGO shall be established by using an appropriate model.

e. If the risk analysis shows that the risk of the occurrence of POGO is too high, the dynamic coupling characteristics shall be changed.

NOTE One way to satisfy this requirement is by implementing an anti-POGO device.

f. The design of the feed system and anti-POGO device shall prevent any occurrence of POGO.

g. As the anti-POGO device can cause gas injection into the feed system, it shall be ensured that this has no adverse effect on the engine operation.

h. Mathematical modelling specified in 6.6.7.3.3 shall be reported in accordance with Annex K.

#### 6.6.7.4 Gimbaling and expansion compatibility

##### 6.6.7.4.1 General

a. The feed system shall be designed such that it enables:

1. engine gimbaling,
2. system expansion–contraction due to changes in temperature and loads;

b. The feed system shall not adversely affect the flow.

##### 6.6.7.4.2 Gimbal bellows

Measures shall be taken to avoid water condensation and subsequent icing on the bellows which prevent engine gimbaling.

#### 6.6.7.5 Vapour lock

a. The design of the propulsion system shall be such that the local static pressure does not drop below the liquid vapour pressure due to high flow velocities or temperatures.

b. The propulsion system shall prevent any gas being trapped which leads to vapour lock.

#### 6.6.7.6 Geyser effect during pre-launch activities

The geyser effect in the lines shall be avoided by thermally insulating the feed system, or by operational procedures where the propellant in the line is replaced by colder propellant.

NOTE For cryogenic propellants especially, the propellant feed system can become heated during launch preparation – delay. This causes the cryogenic propellant to form vapour bubbles in the lines, which while rising, cause a geyser effect.

## 6.6.8 Liquid engines: functional system analysis

### 6.6.8.1 Reporting

The reporting shall be in accordance with Annex C.

### 6.6.8.2 General

#### 6.6.8.2.1 Engine requirements

The engine requirements shall conform to the mission requirements.

NOTE The engine layout and configuration is subject to various constraints with regard to the system requirements. Therefore, there are a large number of potential solutions that conform to the system requirements. The performance of an engine is affected by the layout, overall architecture, the technology level and the selected manufacturing processes. The latter can introduce additional constraints.

#### 6.6.8.2.2 Global performances

In addition to the requirements in subclause 4.3.2, the provisions in the following subclauses apply to liquid rocket motors for launchers.

The engine thrust is the vectorial sum of the thrusts generated by all engine components:

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

### 6.6.8.3 TCA performance: general

a. The thrust chamber assembly (TCA) and its performance parameters shall be taken into account in the engine design, as it delivers the largest part of the engine thrust.

NOTE 1 As for the engine, the main performance parameters for the TCA are:

- the thrust,
- the specific impulse, and
- the burn time.

These are defined in the same way as for the engine, in particular the mass flow rate, the momentum and enthalpy flux entering and leaving the TCA, and the inlet and outlet pressures acting on the TCA.

NOTE 2 The thrust and performance of the TCA are affected by:

- the efficiency of the combustion process, and
- the efficiency of the acceleration and expansion process of the combustion products in the chambers, the throats and the nozzle extensions.

b. The values of the performance parameters ($I_{sp}$, $C^*$, $C_F$), for every operational point of the TCA, shall be determined.

NOTE A traditional approach is to separately consider the contributions of the combustion chamber, $C^*$, and the nozzle, $C_F$, to the specific impulse, $I_{sp}$. Other approaches can also be used.

c. All losses and gains specified in 4.3.2, 6.6.8.4, 6.6.8.5, 6.6.8.6 and 6.6.8.7 shall be taken into account in determining or assessing the real specific impulse, independently of the analysis approach taken.

#### 6.6.8.4 TCA performance: characteristic velocity - losses and gains

##### 6.6.8.4.1 Deviations in propellant composition

If the composition of the propellant deviates from the nominal composition, the effect shall be determined by making a theoretical $C^*$ calculation taking the actual propellant composition into account.

NOTE 1 For the theoretical characteristic velocity ($C^*$) calculations, usually, the nominal propellant composition is used.

NOTE 2 Typical causes for deviations in propellant composition are: dissolution of pressurant gases, contaminants that can stem from the manufacturing process, storage and chemical reactions with the tank walls and tubing.

NOTE 3 Propellant specifications give the maximum amount and nature of contaminants that are introduced in the production process.

##### 6.6.8.4.2 Kinetic effects

a. Kinetic losses should be taken into account when assessing the optimum mixture ratio.

NOTE The effect of finite chemical kinetics can be estimated using one of the following methods:

- By taking the dimensions of the combustion chamber into account, using a kinetic calculation, and the same reactions and species used in the ODE-type calculation, provided that the kinetic data is available, and assuming a priori ideal mixing.
- By using experimental data which relates the performance of similar engines to the $L^*$, pressures and mixture ratios of these engines.

The usual approach for estimating the theoretical $C^*$ is by using an ODE-type calculation. This assumes that complete combustion is reached in the combustion chamber.

This assumption can lead to severe deviations in particular for engines:

- at low chamber pressure,
- using hydrazine-based propellants, or
- with small characteristic length, $L^*$.

b. If a. is not met, justification shall be provided.

##### 6.6.8.4.3 Combustion pressure loss

a. The pressure loss due to combustion in the chamber may be determined by assuming or calculating a (small) Mach number at the injector plate and calculating the Mach number at that position in the combustion chamber where it is assumed that the combustion is complete.

NOTE The latter Mach number is deduced from an isentropic relation between this Mach number and the Mach number at the throat.

b. The relation between the injector plate Mach number and the Mach number at the position where the combustion is assumed to be complete shall be used to estimate the loss in total pressure.

c. In the calculation described in b., ideal mixing shall be assumed.

#### 6.6.8.4.4 Wall heat loss and boundary layer effects

a. The effective enthalpy loss which results from the heat transferred from the combustion chamber to the walls shall be taken into account to correct the theoretical ODE-type $C^*_{th}$ calculation by changing the propellant input enthalpy.

NOTE 1 Once the cooling and heat transfer analyses have been carried out, the amount of heat transferred from the combustion chamber to the walls can be established.

NOTE 2 Note that the enthalpy is specified at the injector outlet.

b. The following requirements apply to the boundary layer:

1. Friction may be assessed by boundary layer analysis.
2. The boundary layer thickness at the throat may be determined by a boundary layer calculation.
3. The effect of the mixture ratio of the boundary layer on the theoretical $C^*_{th}$, shall be estimated.
4. For the estimation specified in 3., a two stream tube approach may be used where the boundary layer stream tube has one mixture ratio, and the core flow stream tube has another mixture ratio.

NOTE 1 The boundary layer, in addition heat transfer mentioned in a., has the following effects:

- friction that causes a pressure loss;
- the boundary layer thickness at the throat effectively reduces the throat area;
- usually, the boundary layer has a mixture ratio, which is different from the core-flow mixture ratio.

NOTE 2 The boundary layer thickness at the throat is usually small and often hardly affects the performance.

c. If film cooling is used, the same approach as in a. and b. shall be used to correct for film cooling effects on the $C^*_{th}$.

d. The chamber geometry shall be taken into account in the boundary layer analysis.

#### 6.6.8.4.5 Non-uniform flows and multi-phase flow effects

a. Performance losses from non-uniform mixed flows, which have locally different mixture ratios, (e.g. by a multi-stream tube analysis) shall be estimated.

NOTE 1 It is essential that more or less complete mixing is achieved at a distance from the injector plate which is much smaller than the distance from the injector to the nozzle throat, because otherwise large amounts of unburned propellants are ejected.

NOTE 2 Droplets in the flow have the following effects:

- unburned droplets are ejected from the throat, leading to performance losses;
- the droplets have a “drag” effect on the gas phase, lowering the $C^*$;

- the mixture, which for the $C^*_{th}$ calculations has been assumed to be an ideal gas, is no longer an ideal gas, and the gas density has changed compared to the density assumed for the $C^*_{th}$ calculations. Because of this, there is also a misfit in the effective throat area.

NOTE 3 It is very difficult to assess the effect of droplets in the combustion chamber and throat area on the $C^*$. This is, amongst other things, because droplet distributions and droplet size distributions are unknown.

b. The ejection of unburned droplets should be avoided by design and development efforts.

c. If b. is not met, justification shall be provided.

#### 6.6.8.4.6 Hot gas tap-off

a. The effects on the $C^*$ may be assessed by comparative tests or by detailed modelling.

NOTE Hot gas tap-off from the combustion chamber has the following effects on $C^*$:

- If the tap-off is performed intermittently, there is an intermittent mismatch between the throat area and the mass flow rate through the nozzle. This effect, and the reduction in chamber pressure, can be calculated from mass balance considerations.
- Locally, the mixture ratio can be perturbed, resulting in a non-uniform mixture ratio distribution. This effect has been treated above.
- The tap-off can disturb the boundary layer close to the tap-off point and also affect local heat transfer.

b. Mathematical modelling for 6.6.8.4.6.a. shall be reported in accordance with Annex K.

#### 6.6.8.4.7 Ablative wall

The effect of changing the nozzle expansion-contraction ratios may be taken into account by ODE type and kinetic codes.

NOTE The main effect of ablative walls is the changing of the geometry; the chamber diameter increases and the throat area changes with time due to pyrolysis if the throat also has an ablative wall. This affects the expansion and contraction ratio.

In addition it can have the following secondary effects:

- Increase of the mass flow rate as compared to the propellants mass flow rate.
- Change in the composition of the gases in the combustion chamber, and usually, a slightly decrease in the combustion temperature.

#### 6.6.8.4.8 Temperature effects

In all cases, for the $C^*$ calculations, the throat area shall be based on one which takes the equilibrium temperature into account (thermal expansion).

#### 6.6.8.4.9 TCA performance: combustion efficiency

In addition to the $C^*$ efficiency, a combustion efficiency, $\eta_{com}$ is also used, which specifically addresses the efficiency of the injection, vaporization, mixing and combustion process.

The combustion efficiency, $\eta_{com}$, can be obtained using methods similar to $\eta_{C^*}$, but without taking into account the following $C^*$ losses and gains:

- combustion process pressure loss,
- wall heat loss and boundary layer effects;
- film cooling,
- ablative wall effects.

#### 6.6.8.5 TCA performance: thrust coefficient - losses and gains

a. In all nozzle calculations, the geometry, i.e. throat area, expansion ratio shall be based on the operational conditions (temperature at the throat and along the nozzle contour) during the operation.

b. The reporting of the work specified in a. shall be in accordance with Annex G.

c. The actual temperatures used to establish the geometry of the nozzle during the operation or test conditions shall be documented in detail.

NOTE Because of the completely different analyses of the flow fields, two type of nozzles are distinguished for establishing corrections for the $C_F$ determined by the ODE-type calculations:

- conventional nozzles, with a conical or bell-shaped extension;
- non-conventional nozzles, e.g. dual bell nozzles, plug nozzles, or expansion-deflection nozzles.

#### 6.6.8.6 TCA performance: thrust coefficient - losses and gains for conventional nozzles

##### 6.6.8.6.1 Reporting

The reporting of the work specified in 6.6.8.6 shall be in accordance with Annex G.

##### 6.6.8.6.2 Shocks and flow separation

The following provisions apply to estimating the performance of the nozzle.

NOTE Shocks can be induced due to nozzle contouring, boundary layer separation, or a sudden boundary layer displacement (tripping).

The effects of shocks due to contouring, as long as they affect the performance, are already included in the non-uniform flow losses-divergence losses.

Boundary layer separation, in a well-designed nozzle can occur due to an over-expansion that is too large. In the case of a free shock, the performance of the nozzle can be estimated.

a. The separation point may be estimated from existing engineering correlations, taking into account, as a minimum, Mach number effects.

b. The free core flow after the separation point may be assumed to be parallel to the nozzle axis, with a constant exhaust velocity.

c. In the area between the nozzle wall and the free core flow, the pressure is slightly lower than the ambient pressure (80 % – 95 % ambient pressure) due to the inflow of ambient air, it may also be estimated from engineering correlations.

NOTE Restricted shock separation is characterized by a re-attachment of the flow field after the separation region. Due to the complex flow structure after the re-attachment, only a detailed flow analysis enables the reduction in thrust to be

estimated. Re-attachment only occurs in nozzles featuring an internal shock due to contouring and results from the interaction of the inverse Mach reflection of the internal shock at the centreline with the separation shock.

#### 6.6.8.6.3 Ablative wall and transpiration cooling

The effects on performance shall be estimated by solving the boundary layer equations with distributed mass addition and determining the momentum loss thickness.

NOTE Ablative walls and transpiration cooling increase the mass flow rate compared to the propellant mass flow rate. The boundary layer temperature decreases.

#### 6.6.8.6.4 Two-phase flows

The following effects of condensation shall be taken into account to assess their effect on $C_F$.

a. Propellant droplets in the flow originate from insufficient mixing, atomization, vaporization and combustion.

NOTE Their main effect on performance is a drag effect, reducing the effective exhaust velocity.

b. Very large expansion in the nozzle that causes condensation of one or more species.

NOTE Although, in most cases, the condensed droplets or solids are very small and do not lead to a significant momentum transfer between condensed species and gas, there are two effects of condensation that affect nozzle performance:

— the mean density of the nozzle flow increases;

— there is an energy transfer (heat of condensation) from the condensed species to the gaseous species.

#### 6.6.8.6.5 Re-injection of gases

The effect on the thrust coefficient can be estimated by a two stream tube model (see Figure 6), ignoring the mixing of core flow and re-injected flow.

NOTE 1 Re-injection of, for example, turbine exhaust gases, TEG, or dump cooling gases have the following objectives:

- better use of re-injected gases (increase of $I_{sp}$);
- serve as a film cooling layer.

NOTE 2 Navier-Stokes type computer models or other more refined calculations enable the mixing of the injected gases and the core flow to be accounted for in assessing the effect on $C_F$.

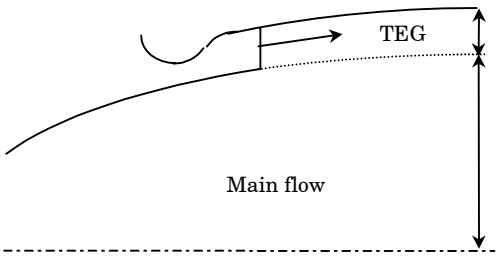



**Figure 6: Two stream tube model**

6.6.8.6.6 Film cooling

a. Gaseous film cooling may be treated in the same way as, either: the re-injection of gases (see 6.6.8.6.5), or ablative cooling (see 6.6.8.6.3).

b. Liquid film cooling shall consider the evaporation and decomposition of the liquid film and its transformation into a gaseous film.

c. The transformation of a liquid film into a gaseous film may be treated in the same way as ablative cooling (see 6.6.8.6.3).

NOTE Navier-Stokes flow analyses (2-D or 3-D) account for mixing effects.

6.6.8.6.7 Additional losses

a. The losses introduced by 3-D flow effects (swirl and rotational flow) should be assessed.

b. If a. is not carried out, justification shall be provided.

### 6.6.8.7 TCA performance: thrust coefficient - losses and gains for non-conventional nozzles

6.6.8.7.1 Reporting

The reporting of the work specified in 6.6.8.7 shall be in accordance with Annex G.

6.6.8.7.2 Dual Bell nozzle

During the over-expanded operation mode, where the separation is anchored at the wall inflection point, the performance can be estimated similarly to a conventional bell nozzle with free shock boundary layer separation.

NOTE 1 The divergence loss or non-uniform flow analysis accounts for the imperfect contour in the case of the full flowing nozzle (flow attached everywhere). The divergence loss is estimated in the same way as conventional bell nozzles.

NOTE 2 Figure 7 shows a schematic representation of a dual bell nozzle.

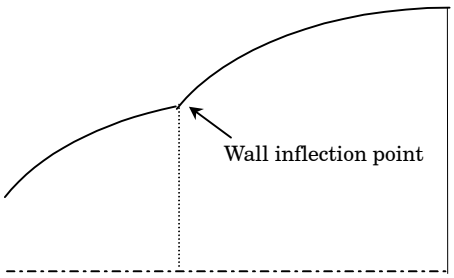



**Figure 7: Schematic of a dual bell nozzle**

6.6.8.7.3 Extendable nozzle cones

To have relatively short nozzles when an upper stage is still integrated with the launcher, but with the advantage of a large expansion during motor operation, systems exist that increase the nozzle extension. Typical examples are:

- One or more deployable skirts. These skirts are initially stowed around the exit cone, and move down along guidance rails to increase the expansion ratio and length of the exit cone.
- Flaps that are folded over the exit cone and are deployed to increase the expansion ratio and length of the exit cone.

- Shingles that are initially positioned on the exit cone and for deployment slide down along guidance rails to increase the expansion ratio and length of the exit cone.
- A cone folded within the exit cone. This cone folds out as a consequence of the ignition pressure to increase the expansion ratio and length of the exit cone.
- A combination of two or more of the above systems.

Some systems can also be used for a first stage and deployed at an optimum moment during ascent.

6.6.8.7.4 Plug nozzle

One objective of a plug nozzle is the continuous adaptation of the expanding flow over a wide range of pressure ratios. This is accomplished by guiding the expanding flow over a central core (plug) and having on the outside a free jet boundary. While the plug nozzle lends itself to a proper analysis of the performance under nominal (design) conditions, a proper performance analysis of off-design conditions cannot be performed without a detailed fluid dynamic analyses. No accurate engineering correlations are available for off-design conditions.

6.6.8.7.5 Expansion-deflection nozzle

The expansion-deflexion nozzle is an "inverted" plug nozzle where the free stream boundary forms the central core, and the flow is guided by an outside contour. The adaptation of the flow is limited to a smaller range of pressure ratios than for the plug nozzle. As for the plug nozzle, nominal performance (design conditions) lends itself to analysis. Off-design performance cannot be done without a detailed fluid analyses.

### 6.6.8.8 Reference point and envelopes

If a rocket engine is expected to operate in disconnected envelopes (qualification envelopes which do not overlap) the following requirements apply.

a. The engine shall be qualified in each envelope separately.

b. It shall be ensured that a transition between the two envelopes can be made.

c. The transient process specified in b. shall be qualified.

### 6.6.8.9 Transients

6.6.8.9.1 Reporting

Transient analyses specified in 6.6.8.9 shall be in accordance with Annex I.

6.6.8.9.2 Chill-down

a. The mass flow rate for cooling down the engine systems, subsystems and components shall be determined by:

   1. the time specified to reach the specified temperature,
   2. the occurrence of temperature gradients in components, subsystems or systems.

   NOTE Chill-down is applicable to cryogenic engines. The objective is to ensure that all components that come into contact with cryogenic propellants during start-up are being cooled down to such temperatures that the proper liquid propellant condition is ensured.

b. The effect of cooling during chill-down on components that need not be cooled, shall be taken into account for these components.

c. In the case of chill-down by GSE, perturbations and instabilities due to the transition between GSE and on-board systems shall be prevented.

d. During in-flight chill-down, non-propulsive vents should be used.

e. If d. is not met, justification shall be provided.

f. It shall be ensured that the in-flight chill-down does not generate forces or moments that are incompatible with the ACS capabilities.

g. It shall be ensured that the vented propellants do not exceed the limits for mechanical or thermal loads and shall not affect parts of the launcher or payload (e.g. corrosion).

6.6.8.9.3 Start-up

a. During the start-up, when the rocket engine undergoes a transient process from no operation to steady state operation at its nominal conditions, and the systems, subsystems and components pass through regimes outside the steady state operational envelope, it shall be ensured that this transition is smooth.

b. It shall be ensured that the ignition of the engine and the control of the mixture ratio satisfy an engine specification conforming to 4.2.e. (see also 6.6.9.3.2.b.).

c. The interface between stage behaviour and engine behaviour shall be taken into account when testing an engine on a test stand for start-up behaviour.

d. It shall be ensured that any dynamic effect, generated during start-up, is kept within the specified ranges for the stage and launcher.

6.6.8.9.4 In-flight transients

a. In flight transient within one operational envelope

   During the transient between two operational conditions within one operational envelope, the following apply:

   1. It shall be ensured that non-stationary effects do not adversely affect the motor operation.
   2. Requirement 1. shall be verified by tests.
   3. Requirement 1. should be verified by supplementary analysis.

b. In-flight transient between two non-connected operational envelopes

   During the transient between two non-connected operational envelopes, the following apply:

   1. It shall be ensured that the transient:
      (a) is fast enough so as not to create anomalous behaviour;
      (b) does not generate loads that exceed the system requirements;
      (c) does not adversely affect the engine operation.
   2. Requirement 1.(c) shall be verified by tests.
   3. Requirement 1.(c) should be verified by supplementary analysis.

6.6.8.9.5 Nominal shutdown

a. Nominal shutdown shall be performed under the following conditions:

   1. the stage has reached the specified trajectory parameters;
   2. the propellant has reached a level where, if the engine is not shut down, it can be badly damaged (especially for cryogenic engines);
   3. the engine has completed a test run.

b. During shutdown the mixture ratio shall be controlled.

c. For a fuel rich engine the oxidizer should be shut down first.

d. It shall be ensured that during nominal shutdown the transition is smooth.

NOTE During shutdown the engine undergoes a transient process from steady nominal operation to no operation and the system, subsystems and components pass through regimes outside the steady state operational envelope.

e. It shall be ensured that any dynamic effect, generated during nominal shutdown, shall be in conformance to the stage and launcher requirements.

f. For tests on a test stand, after shutdown the engine, its piping, lines and coolant loops shall be purged by $N_2$ or He.

6.6.8.9.6 Emergency shutdown

Emergency shutdown on ground shall be performed when anomalies are detected when the engine is on a test stand, or a launcher on a launch pad.

NOTE 1 Emergency shutdown on ground is primarily performed to prevent damage to the test stand or the launch pad. A secondary objective is to save the engine or the launcher.

NOTE 2 Emergency shutdown in flight can be performed with the objective of:

- recovering the launcher after fall down;
- saving lives;
- recovering the launcher in the case of re-usable launchers.

6.6.8.9.7 Thrust decay

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

6.6.8.9.8 Tail-off

a. To avoid impact of a burnt-out stage with the higher stage during the separation phase, the tail-off of the lower stage and the engine shall be determined, so that the proper moment of ignition of the higher stage can be defined.

b. The tail-off characteristics shall be reproducible so that accurate information on the total impulse can be obtained.

#### 6.6.8.10 Thermal-mechanical aspects

a. The layout shall conform to the system and subsystem requirements with regard to the geometrical envelope.

b. The layout of the high-pressure lines shall be such that the risk of failures in a line inducing failures in other lines is minimized.

NOTE For risk management refer to ECSS-M-00-03.

c. The layout of oxidiser and fuel lines shall be such that the risk of failures or leaks in the oxidiser or fuel lines, respectively, causing failure or fires due to the closeness of the fuel or oxidiser lines, respectively, are minimized.

NOTE For risk management refer to ECSS-M-00-03.

d. Curvatures and diameters of propellant lines shall be such as to ensure flow conditions and pressure losses within the specified limits.

NOTE Strong curvatures and small diameters adversely affect the flow conditions and pressure losses.

e. A trade-off to determine the number of joints shall be made taking into account the following:

1. the number of joints with respect to leakage risk;
2. the ease and cost of exchanging components and lines;

3. the additional mass of the joints;
4. the overall costs.

f. The layout shall ensure that the temperature differences between adjacent components or parts are maintained below the specified limits.

NOTE This is especially relevant for sensitive measurement equipment and sensitive components.

g. The layout shall take into account the following aspects:
1. easy replacement of equipment, components and transducers;
2. potential thermal or mechanical deformations, to avoid undesired contact or interference between components, equipment, subsystems and systems;
3. implications on the cost;
4. manufacturing tolerances;
5. the engine inertia, COM, stiffness and dynamic response requirements.

### 6.6.9 Liquid engines: thrust chamber assembly

#### 6.6.9.1 General

##### 6.6.9.1.1 Overview

The thrust chamber has 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.

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

- to support components and subsystems;
- 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,
- the coolant system,
- the nozzle.

##### 6.6.9.1.2 Global geometric design

a. The internal shape of the TCA shall result from a flow and combustion analysis and optimization taking into consideration, as a minimum, the following parameters:
1. The length (distance from injector plate to throat).
2. The total length (the distance from the injector place to the nozzle exit).
3. The contraction ratio.
4. The throat diameter.

5. The area ratio.

NOTE The design of the TCA is strongly linked to a global engine design optimization.

b. When establishing the overall engine geometry, the geometrical boundaries of the systems and subsystems shall be taken into account.

c. The TCA design shall take into account the following in conformance to the system requirements:

1. the performance and optimization;
2. the overall engine mass;
3. cost;
4. the selected cycle and heat transfer;
5. the total engine length.

6.6.9.1.3 Structure

a. The design process shall lead to a definition of a TCA structure that includes the definition of:

1. the materials,
2. the mass,
3. the wall thicknesses.

b. The structure shall be such that the systems, subsystems and components (e.g. turbo pumps, valves, joints, actuators, and transducers) can be mounted.

c. The structure shall ensure the integrity of the TCA during its mission.

d. The following parameters shall be taken into account in the design of the structure of the TCA:

1. its life and number of cycles;
2. operating time;
3. temperatures;
4. pressures;
5. compatibility of structural material with propellants and combustion gases;
6. compatibility of the structural materials with one or more propellants in the case of cooling by propellants;
7. the selected coolant system;
8. loads:
   (a) internal (e.g. pressure, shocks and side loads),
   (b) external (e.g. aerodynamic loads, acoustic loads, buffeting, and loads due to ground tests for development and qualification);
9. thermal loads (e.g. radiative and convective);
10. inertial loads (e.g. accelerations and vibrations);
11. thermo-mechanical loads, including creep effects.

6.6.9.1.4 Fatigue and creep

a. The following analysis should be made:

1. fatigue behaviour of the structure;
2. creep behaviour of the material.

b. If a. is not carried out, justification shall be provided.

c. If TVC actuators are attached to the nozzle, the nozzle stiffness shall be in conformance with the TVC requirements.

6.6.9.1.5 Buckling

a. A comprehensive buckling analysis of the nozzle extension under both on-ground and in-flight combined loads shall be made.

b. If the nozzle is made out of different sections:

   1. A detailed thermo-mechanical analysis of the connections between the sections shall be made.

   2. It shall be ensured that the connections between sections conform to the leak tightness requirements during the mission.

### 6.6.9.2 Injector

6.6.9.2.1 General

The main functions of the injector are:

- to receive the propellants and to distribute these over the injection elements;
- to inject the propellants;
- to atomize the propellants;
- to provide the conditions for enhancing the mixing of the propellants;
- to provide the conditions that contribute to stable combustion.

The main components of the injector are:

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

6.6.9.2.2 Design

a. In the injector design, the presence of contaminants in the propellants shall be taken into account.

b. The injector head pattern shall be designed such that the resulting flow and heat transfer are compatible with the other thrust chamber components.

c. The design of the injector feed system (e.g. dome and manifolds) shall

   1. take into account the requirements on start-up and shutdown;

   2. conform to the geometrical requirements.

d. The design and layout of the cavities at the entrance of the injector elements shall ensure the same conditions at the entrance of injector elements of the same kind.

e. The design of the fluid passages (volumes) between the engine valves and the injector elements shall be such that under start-up and shutdown conditions, the fluid flow is reproducible.

f. The design of the injector shall ensure that there are no propellant traps.

   NOTE This enables proper draining.

g. The design shall take into account contamination with atmospheric moisture.

   NOTE 1 This is especially important for cryogenic engines.

   NOTE 2 Small cavities, especially, have a tendency to trap condensed water or ice.

h. The design of the injector and combustion chamber shall ensure that dissimilar propellants are not mixed within the injector.

i. Grids, deflectors or other devices to distribute the flow evenly within the dome should be used.

j. If i. is not met, justification shall be provided.

#### 6.6.9.2.3 Selection of injection elements: overview

There is a large variety of injection elements, such as impinging (e.g. unlike, doublet, triplet, multiplet), coaxial, swirl-coaxial and pintle, on which a choice can be based.

Coaxial elements are often used for gas-liquid propellant combinations, e.g. cryogenic engines.

Impinging and swirl elements are often used with storable propellants.

Swirl-coaxial and impinging injector elements are often used with gas-gas propellant combinations.

#### 6.6.9.2.4 Selection of injection elements: basis for the selection

The selection of a particular injection element shall, as a minimum, be based on the following:

a. the physical properties and state of the propellants: i.e. gas, liquid, temperature, density, pressure and viscosity;

b. the state of the two propellants, i.e. gas-gas, gas-liquid, liquid-liquid;

c. the interaction of the propellants, i.e. hypergolic or non-hypergolic;

d. the expected performance;

e. an injector pressure drop which prevents amplification of thrust chamber combustion instability by interaction with the feed system;

f. the tolerance with regard to contaminants in the propellants;

g. (company) experience and database;

h. costs and ease of manufacturing.

NOTE 1 A good performance of a specific type of injection element in one engine configuration does not guarantee that this type of element also performs well in a different engine configuration. Also, the distribution of injection elements over the injector plate itself is known to affect the flow and combustion behaviour. The flow and combustion process in the vicinity of the chamber walls has a strong effect on the heat transfer into the wall, while the presence of the wall may strongly interact with, and affect the flow and combustion process.

NOTE 2 Small changes or modifications in the injector element can result in very different flow and combustion behaviour in the rocket engine.

NOTE 3 The distribution of the injection elements over the injector is known to have a strong influence on the combustion, stability, thermal behaviour and performance of the TCA.

NOTE 4 Reducing the dimensions of an injection element leads to shorter mixing lengths and usually better combustion efficiency in the same combustion chamber. However, costs increase with the number of elements used.

NOTE 5 Only tests on a full scale combustion chamber enable to verify the proper functioning of the combination of injector and combustion chamber in terms of $C^*$-efficiency and combustion stability.

#### 6.6.9.3 Igniter

##### 6.6.9.3.1 Overview

The igniter is related to the ignition transient (see 6.6.8.9) and the TCA (see 6.6.9). The main function of the igniter is to provide energy or power to ignite the propellants in the combustion chamber. A secondary function can be to preheat the chamber and cooling jacket.

The ignition system can be dependent on the propellants, i.e. the igniter uses one or both propellants, or is independent of the propellants, in which case separate propellants are used to create high temperature gases. Table 4 gives an overview of some igniter types and whether these are dependent or independent of the main propellants.

**Table 4: Overview of some igniter types and relationship with main propellants**

| Igniter type | Independent of main propellants | Dependent on main propellants |
|---|---|---|
| Pyrotechnic | × | |
| Electric (direct) | | × |
| Electric (torch) | × | × |
| Acoustic | × | × |
| Catalytic | × | × |
| Hypergolic | × | × |
| Ground torch | × | |

If the igniter immediately ignites the main propellant flow, there is a very strong dependency of the ignition process on the start-up sequence (i.e. opening of valves, main mass flow rate history).

The pyrotechnic igniter produces hot gas from a pyrotechnic type material.

The electric (direct) igniter is a spark plug that ignites the main propellants directly.

The electric torch uses a spark plug, that ignites a propellant flow which subsequently ignites the main propellants. An additional advantage is that the spark plug then is shielded from the hot combustion gases in the main chamber.

The acoustic (or resonance) igniter creates a hot gas by a resonance phenomenon; the hot gas is subsequently mixed with one or more gases which together form a combustible mixture. This mixture ignites due to the high temperature created in the resonance cavity.

The catalytic igniter ignites a combustible gas mixture or liquid upon contact which creates a hot flame. The igniter can either catalytically ignite the main propellants, or catalytically ignite a separate propellant or propellant combination to create a hot flame.

The hypergolic igniter uses a hypergolic propellant combination to create a hot gas flame. The hypergolic propellants, in the case of a separate igniter, are stored separately from the main propellants.

The ground torch igniter makes use of a torch that is present on the ground and for safety reasons burns off fuel spilled from the launcher. This torch can serve as a back-up ignition system in case of failure of the main igniter or as a main ignition system for first stages.

6.6.9.3.2 Normative provisions

a. To ensure good ignition of the propellant mixture in the vicinity of the injector face plate for the extreme envelope, it shall be ensured that the igniter provides either:
   - power,
   - energy (thermal or chemical), or
   - both.

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

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

d. It shall be ensured that requirement c. leads to a complete ignition of the propellant mass flow rate in the combustion chamber.

   NOTE For igniters producing a flow of hot gases, this requirement specifies the mass flow rate and temperature.

e. If the ignition limits of the mixture to be ignited are not known, these shall be established: e.g. pressure, temperature, mixture ratio, local velocities.

f. The length of time that the igniter shall function shall be specified.

g. The number of ignitions to be performed by the igniter during a mission and the related conditions shall be specified.

h. The total number of ignitions to be performed by the igniter during its life shall be specified.

i. If not specified, the following margins shall be established for the ignition system to ensure good ignition of the propellant mixture:
   1. power;
   2. energy;
   3. the time during which the igniter functions.

j. The operating time of the igniter shall conform to the conditions that ensure an ignition of the propellant mixture that conforms to 6.6.9.3.2.c.

k. For hot gas flow igniters, good mixing between the mixture to be ignited and the igniter gases shall be ensured.

   NOTE Thorough mixing implies that the variation in concentrations of the various species is in accordance with a standard conforming to 4.2.e.

   This can be realized, for example, by introducing a radial component into the hot gas flow, or by introducing a swirl.

   Most rocket engines operate in fuel rich conditions. If hot gas flows are used for ignition not only the temperature, but also the composition of the igniter gases is important.

l. If the igniter flow is not purely in an axial direction, it shall be ensured that the chamber walls are not damaged by the igniter flow.

m. If not specified, criteria for igniter reproducibility shall be established.

n. It shall be ensured that the following variables satisfy the reproducibility criteria:
   1. the power delivered by the igniter;
   2. the energy delivered by the igniter;
   3. the igniter response time;
   4. the composition of the igniter gases.

o. Manufacturing of the igniter shall ensure that the specified tolerances are met.

p. 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.

q. The following shall be taken into account in the selection of the igniter type:

1. the experience available;
2. the costs;
3. the development time;
4. the additional equipment to be used (e.g. propellant tanks, gas tanks, feed lines, high-voltage electric power supply, and safe and arm device);
5. the mass;
6. the reliability.

r. The extreme envelope of the conditions to which the igniter can be exposed during the mission shall be defined.

s. The extreme envelope for the functions of the igniter shall be established.

NOTE These two extreme envelopes can be different.

t. If the engine conditions deviate from those specified for the functioning of the igniter (e.g. propellant temperatures too low), measures shall be taken to restore the igniter conditions to the specified ones before operating the igniter.

u. The measures specified in s. shall be qualified.

v. The igniter design shall conform to the extreme envelope for the engine during the whole mission.

NOTE For pyrotechnic igniters, see ECSS E-30 Part 6.

#### 6.6.9.4 Combustion chamber

##### 6.6.9.4.1 General

a. The combustion chamber shall:

1. conform to the system requirements;
2. provide a volume for efficient combustion of the propellants;
3. enable the combustion gases to attain the specified temperatures and pressures;
4. enable the engine turbo machinery to be powered in the case of expander, bleed, and tap-off cycles;
5. if specified, enable the provision of gases for tank pressurization;
6. sustain all loads including thrust;
7. transmit forces and torques to the stage.

b. The outside of the combustion chamber shall:

1. conform to the geometrical requirements and constraints,
2. conform to the thermal requirements of the interfaces.

##### 6.6.9.4.2 Combustion instability: overview

Combustion instability in liquid rocket engines is related to:

- the feed system, or
- the combustion process.

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.

Instabilities related to feed systems encompass POGO (6.6.7.3) but there can also be a coupling between the feed system and pressure fluctuations in the chamber (chugging) if the injector pressure drop is smaller than the pressure fluctuations in the chamber.

Combustion instabilities related to the combustion process are usually high frequency acoustic oscillations. They are related to the mixing and evaporation processes. In chambers with very small residence times, low frequency, combustion related oscillations can occur.

6.6.9.4.3 Combustion instability: general

a. It shall be demonstrated that any oscillation in the engine
   1. does not damage the engine,
   2. does not adversely affect the engine performance,
   3. conforms to the system and subsystem requirements.

b. As combustion instabilities in liquid rocket engines usually occur as oscillatory combustion (limit cycle) the following apply:
   1. The acoustic modes in the chamber should be determined at an early design stage (phase A and B).
   2. It shall be ensured that the eigenfrequencies of the chamber do not coincide with other engine eigenfrequencies (e.g. feed system).
   3. It shall be ensured that the delays in vaporization or heating do not create instability problems, e.g. temperature of hydrogen.

      NOTE This can occur if one of the propellants uses much more heat for the vaporization or heating than the other, even under extremely low temperatures,

c. If b.1. or b.2. are not satisfied, justification shall be provided.

6.6.9.4.4 Combustion instability: damping devices

Combustion instability damping devices shall

a. increase the engine stability margin,

b. suppress the growth of oscillatory combustion,

c. dampen pressure oscillations, and

d. limit the amplitude of pressure oscillations to values that conform to the engine requirements.

6.6.9.4.5 Combustion instability: tests

Instrumented test motors shall demonstrate that the motor is statically and dynamically stable by demonstrating the following:

a. under extreme pressure, temperature and mixture ratio conditions, no combustion instability occurs (static stability);

b. the engine margins conform to the engine and subsystem and system requirements (static stability);

c. the engine remains stable after a perturbation, e.g. bomb testing, ramping, bubble ingestion (dynamic stability).

### 6.6.9.5 Coolant system

6.6.9.5.1 Overview

TCAs can be cooled in many different ways. Most common are:

- regenerative cooling,
- dump cooling,

- film cooling,
- transpiration cooling,
- radiation cooling,
- ablative cooling,
- a combination of some of the methods.

In addition coatings can be used to create a thermal barrier; this is often used in combination with the cooling systems.

The mixture ratio close to the walls can be adjusted (trimming) to reduce heat transfer to the walls.

6.6.9.5.2 General

a. The design of the cooling system shall:
   1. select a material or combination of materials;
   2. limit the material temperature such that the TCA conforms to the mission requirements;
   3. take into account the overall costs;
   4. take into account the performance;
   5. take into account the possibility of performing ground tests.

      NOTE This can result in a TCA with different sections, employing different cooling methods.

b. To conform to a., the following shall be taken into account:
   1. the TCA life;
   2. the number of cycles;
   3. the mechanical loads;
   4. the heat load;
   5. the compatibility with propellants and combustion products;
   6. the material properties.

      NOTE In a number of applications, the coolant system also provides power to the engine power pack or pressurant gases to the tanks. This is often the case for fluid coolant systems.

c. In the design of fluid coolant systems the following parameters shall be taken into account:
   1. pressure drop along the coolant channels;
   2. temperature rise along the coolant channels;
   3. the effect on the engine performance ($I_{sp}$).

d. In the design of fluid coolant channels, film boiling and coking shall be avoided.

e. The design of the coolant channels shall
   1. take into account (company) experience, and
   2. ensure leak tightness.

f. The dispersion between the mass flow rates of the various individual channels of a regenerative cooling system shall be so small that the overall performance requirements of the engine are met.

g. The strong impact that the nozzle wall temperature has on the nozzle boundary layer characteristics, and the strong effect that it has on the friction loss, should be taken into account early in the design phase (project Phases A and B).

h. The special procedures used during the restarting of the hot engine to avoid blockage of coolant channels and to ensure the possibility of establishing a coolant film should be taken into account in the design phase (project Phases A and B).

i. A performance analysis trade-off shall be made between the nozzle wall temperature, and its implications on nozzle design, and the nozzle performance loss.

NOTE Injection of a coolant film (e.g. turbine exhaust gas injection) can be very effective in reducing heat transfer. However, the characteristics of the injected coolant film have a strong effect on the effectiveness of the coolant film and the performance gains or losses.

j. If a coolant film is injected:

1. it shall be ensured that any torque that can be introduced by the injection conforms to the engine requirements;
2. the coolant film should be supersonic;
3. the static pressure at the injection point should conform to the local static pressure;
4. the injection manifold for the coolant film shall not introduce any circulation in the flow;
5. If j.2. or j.3. are not met, justification shall be provided.

k. The evolution of the coolant system during the mission should be taken into account.

NOTE 1 Specially, the hot side surface roughness of the wall can substantially change and thus affect heat transfer.

NOTE 2 The cooling system hydraulic characteristics are an important parameter for feed system coupled instabilities (see 6.6.9.7). Especially for cryogenic engines two-phase flows can develop during transients.

l. If k. is not met, justification shall be provided.

#### 6.6.9.5.3 Heat soak-back

a. The effect of the transfer of heat after shutdown of the engine, from the hot parts of the TCA to cooler parts, shall be analysed and taken into account in the complete TCA design.

NOTE Heat soak-back is especially important for radiation-cooled elements, but not limited to these.

b. The radiative heat flux from the TCA shall be established to assess its effect on elements and system components in the vicinity of the TCA.

### 6.6.9.6 Nozzle

#### 6.6.9.6.1 Overview

The functions of the nozzle are:

- to accelerate the combustion gases, thereby creating an additional thrust compared to a combustion chamber without a nozzle extension;
- to sustain all loads, e.g. loads generated by the operation of the engine, loads generated by the system and subsystem during the mission and handling loads;
- to transmit forces and torques.

6.6.9.6.2 General

a. The geometry of the nozzle shall conform to the geometrical requirements and constraints.

b. The nozzle shall conform to the operational constraints.

c. The nozzle shall conform to the interfaces, including geometrical, thermal and mechanical interfaces.

6.6.9.6.3 Design

a. The design of the nozzle shall take into account the following:

1. nozzle performance;
2. nozzle mass;
3. heat transfer, accounting for the engine cycle;
4. length and diameter,
5. the occurrence of shocks and flow separation.

NOTE 1 The main geometric parameters that determine the shape and dimensions of a nozzle are:

- the maximum length that can be used,
- the maximum diameter that can be used,
- the diameter of the throat.

NOTE 2 The maximum length and diameter can depend on the geometrical interfaces and boundaries (see 4.2.4.5). The design of the nozzle shape is strongly linked to an optimization process, maximizing thrust.

b. The design should take into account any torque or asymmetric effect that can be introduced by the nozzle (e.g. boundary layer interaction with spirally wound coolant channels, and tangential fluid injection).

c. If b. is not met, justification shall be provided.

6.6.9.6.4 Fluid injection system

Fluid injection is not commonly used on liquid rocket engines. It can be considered for plug nozzle TVC. Injection fluids can be reactive (e.g. $O_2$, $N_2O_2$) or inert (e.g. $N_2$).

### 6.6.9.7 Interfaces

a. The engine architect shall take into account the following interfaces and their impact on the design and managerial responsibilities:

1. Interfaces of the TCA with the other subsystems and systems:
   (a) the propellant supply lines, and
   (b) the thrust transfer interface.
2. For non-hypergolic liquid engines, the command interface to power the igniter.
3. In addition:
   (a) other fluid interfaces;
   (b) the power pack interface if one or more turbo pumps are present;
   (c) the TVC interface if the engine has a TVC system;
   (d) the interface with the measurement equipment;
   (e) the interface to tap-off gases;
   (f) interfaces for other equipment;
   (g) interfaces to handle and transport the TCA.

b. The primary variables for all interfaces shall be clearly defined.

c. The primary variables for all interfaces should be verifiable.

d. If c. is not met, justification shall be provided.

NOTE 1 Pressure and velocity distributions are affected by downstream conditions which, when not reproduced exactly can prevent a proper verification.

NOTE 2 Transient phenomena, boundary layer development and stratification are not usually defined for interfaces; nevertheless, these can have a strong effect on the mean values of parameters.

## 6.6.10 Liquid engines: powerpack

### 6.6.10.1 Turbo pump architecture and functional aspects

#### 6.6.10.1.1 General requirements and constraints

a. The pump, shall deliver propellants at the specified ranges of:

1. mass flow rate,
2. pressure,
3. temperature, and
4. state (e.g. homogeneous, free of gas bubbles, and dissolved gas).

NOTE The pump receives propellants in a specified range or state (e.g. pure liquid, liquid with gas bubbles, and liquid with dissolved gas) and range of pressure and temperatures.

b. The turbine shall deliver a specified power to the pump that conforms to the engine and turbo pump requirements and is determined by:

1. the mass flow rate through the turbine;
2. the state of the driving gas ($p$, $T$, composition);
3. the pressure ratio over the turbine, or equivalently, the enthalpy drop, $\Delta H$;
4. the turbine efficiency;
5. the minimum outlet pressure (constraint).

NOTE 1 The turbine efficiency is defined as the ratio of the work delivered to the shaft and the drop from total enthalpy at the inlet conditions to isentropic static enthalpy at the outlet conditions.

NOTE 2 The turbine mass flow rate is limited to a maximum value; the outlet pressure is limited to a minimum value.

NOTE 3 Temperatures are usually limited by the maximum allowable material temperatures.

NOTE 4 The pump receives its power from the shaft. This power is used to pressurize the fluids in the pump. The pump efficiency is defined as the ratio of the increase of the total enthalpy at the pump inlet to the isentropic total enthalpy at the pump outlet and the work delivered by the shaft.

NOTE 5 The turbo pump efficiency is the product of the turbine efficiency, pump efficiency, and mechanical efficiency. The mechanical efficiency accounts for mechanical losses (e.g. gears, bearings).

c. The turbo pump shall conform to the engine system constraints, comprising

1. envelope (geometrical),
2. mass,

3. interfaces,
4. cost.

d. The turbo pump shall:
1. conform to the reliability requirements;
2. be compatible with the working fluids;
3. conform to the system requirements.

#### 6.6.10.1.2 Main parameters

a. An engine and system trade-off shall be performed to determine the need for a boost pump (see also 6.6.10.1.1).

NOTE 1 The necessity of a boost pump can be determined from the input and output conditions, experience (e.g. pump characteristics), observing the dimensional constraints, the number and type of pump stages, and the rotational speed.

NOTE 2 For propellants with a low vapour pressure, the NPSP can be high enough that axial stage (inducer) need not be provided.

NOTE 3 If the NPSP is too low for a suitable pump performance, either a boost pump can be used, or the tank pressure can be increased.

NOTE 4 As a high rotational speed is favourable for the turbo pump performance and size, and a low rotational speed is favourable for avoiding cavitation, the selection of the rotational speed is a compromise.

b. The turbo pump design should include margins that ensure that the pump conforms to the NPSP requirements on completion of the development.

NOTE The NPSP is one of the most critical parameters for the pump design. If the NPSP requirements are not satisfied at the end of the development, either:

- the pump is redesigned,
- a boost pump is installed, or
- the tank pressure is increased.

As these three measures have severe impacts on the system, conformance to provision b. is very important.

c. If b. is not met, justification shall be provided.

#### 6.6.10.1.3 Turbo pump type

The type of turbo pump to be used is to a large extent driven by the volumetric flow rates of the propellants to be pumped. If the volumetric flow rates are of the same order of magnitude, a monoshaft turbo pump often leads to a good solution.

If the volumetric flow rates are very different, the rotational speeds of the pumps are adjusted to optimize efficiencies. There are two solutions:

- Separate turbo pumps: optimized for the fuel and optimized for the oxidizer.
- A geared turbo pump: the pumps are driven by one turbine, but a gearbox enables the pumps to have different (optimized) speeds.

#### 6.6.10.1.4 Turbo pump type selection

a. A trade-off shall be made to select the most suitable type of turbo pump, taking into account the following parameters:
1. system requirements;
2. mass;

3. cost;
4. reliability.

b. If the trade-off specified in a. results in a geared turbo pump being selected:
   1. the system or engine requirements shall be analysed to investigate if a simpler set of the system or engine requirements can be developed which lead to a simpler solution;
   2. the impact of the actions described in 1. shall be analysed.

NOTE 1 Experience shows that implementing a geared turbo pump is complex, and therefore not advisable.

NOTE 2 For further details on requirement engineering see ECSS-E-10 Part 1.

c. In the case of large turbo pumps, gears should not be used.

#### 6.6.10.1.5 Axial arrangement

The principle arrangements for a monoshaft turbo pump are schematically given in the left-hand side of the Figure 8. In (a) the pump $P_1$ pumps the fluid with the severest requirements on NPSP. It anables an inlet duct with no distortion to an inducer directly in front of the impeller.

In (b) the turbine is between the two pumps. In this case the low pressure side of the turbine is adjacent to the high pressure side of pump $P_2$. In (c) this is avoided at the expense of a more complex flow into the pump.

The principle arrangements for single shaft turbo pumps, such as used for separate turbo pumps are shown in (d) and (e).

Note that a pump or turbine in this schematic may indicate a multi-stage pump or turbine.

#### 6.6.10.1.6 Axial arrangement trade-off

a. In selecting the axial arrangement, the following aspects shall be taken into account:
   1. the flow of the fluid into and out of the pumps;
   2. suction performance;
   3. the flow of the fluid into and out of the turbines;
   4. separation between hot and cold elements of the turbo pump;
   5. separation of different propellants and fluids;
   6. separation between high and low pressure sections of the turbo pump;
   7. the possibilities for mounting the components of the turbo pump;
   8. leak tightness along the shaft;
   9. total mass of the turbo pump;
   10. axial balancing of the shaft;
   11. the locations of bearings and the critical speeds;
   12. conformance to the overall geometrical envelope.

b. The location and number of bearings shall be determined taking into account:
   1. the stiffness of the system and the critical speeds;
   2. the technology level of the bearings;
   3. the possibilities for mounting the bearings and the effect on the complexity of the turbo pump;
   4. the possibilities for cooling or lubricating the bearings with propellant;
   5. the unbalanced axial force.

c. Seals shall:

1. prevent any hazardous mixing of different kinds of fluids (e.g. fuel and oxidizer);
2. limit leakage to a level compatible with the system and subsystem requirements.

d. If gaseous barriers (e.g. He, and $N_2$) are used, the gas condition and consumption shall be assessed.

e. Axial balancing shall limit the loads on components of the turbo pump that are in accordance with the mission life and operating conditions of those components.

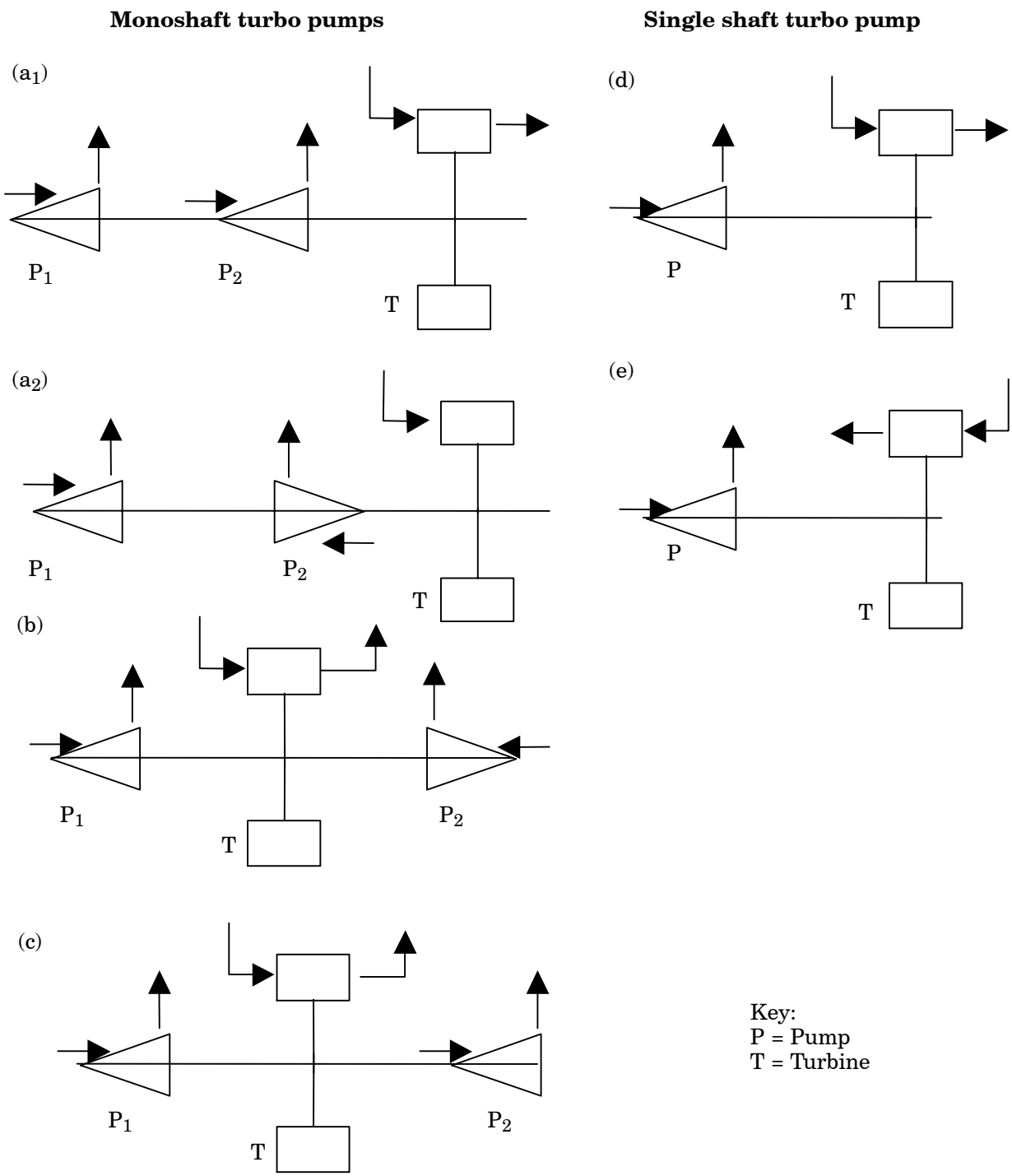



**Figure 8: Turbo pump axial arrangement**

#### 6.6.10.2 Turbo pumps: turbine

##### 6.6.10.2.1 Functional: type of turbine

For a subsonic turbine the relative Mach number with respect to the rotor is smaller than unity.

For a supersonic turbine, the relative Mach number exceeds unity.

As a result, the angle of incidence in a subsonic turbine varies with rotational speed and mass flow rate; therefore, the load distribution on the blades can also vary.

For a supersonic turbine the angle of incidence and the mass flow rate are constant and as a result the load distribution on the blades remains constant.

Usually the losses in a supersonic turbine exceed those in a similar subsonic turbine.

##### 6.6.10.2.2 Functional: selection of the type of turbine

a. The choice shall be made between a subsonic or supersonic turbine with a trade-off of the following aspects:

   1. Cycle (open or closed).

      NOTE In general, in closed cycles, the mass flow rate through the turbines needs not be limited, see 6.6.2.

   2. The number of stages (stator and rotor).
   3. Efficiency (turbine and system).
   4. Mass.
   5. Cost.
   6. Complexity.

      NOTE The reaction ratio of a turbine stage is the ratio of the expansion ratio over the rotor divided by the expansion ratio over the turbine stage. If a turbine has a high reaction ratio this leads to large axial forces.

b. When establishing the reaction ratio of the turbine, it shall be taken into account that, as the relative velocity in reaction turbines (reaction ratio ~ 0,5) is smaller than in impulse turbines, flow losses are reduced, but a reaction turbine uses more stages for the same power that is delivered than an impulse turbine.

   NOTE Most rocket motor turbines have a reaction ratio less than about 0,3.

##### 6.6.10.2.3 Functional: thermodynamic design

a. A trade-off shall determine the type of turbine, its reaction ratio, its rotational speed, its diameter and its number of stages.

   NOTE Normally one or two stages are sufficient.

b. The selection of the blade height shall take into account

   1. the turbine diameter,
   2. the rotational speed,
   3. the mass flow rate,
   4. the material characteristics,
   5. the minimum aerodynamic height, and

6. the reaction ratio.

NOTE The blade height in relation to the gap between blade and housing and the blade aspect ratio strongly influence the turbine efficiency.

c. The turbine diameter shall take into account:

1. the geometric envelope;
2. the blade height;
3. the circumferential speed;
4. the materials.

d. In the turbine design, the losses due to leakage and secondary flows shall be taken into account.

NOTE Because of the relatively small blade height, the losses due to leakage (clearance between blades and turbine housing) and secondary flows are much larger than for terrestrial or aircraft applications. This leads to lower efficiencies.

e. The following requirements apply to the thermodynamic design:

1. Inlet and outlet flow passages shall be taken into account when making a trade-off between the various turbo pump layouts.
2. The effect of flow passages (e.g. curvature, changes in cross-sectional area) shall be taken into account in establishing the turbine inlet and outlet conditions.
3. The turbine outlet flow, at the design point, should be in an axial direction to:
   (a) reduce losses,
   (b) avoid swirl.
4. If 3. is not met, justification shall be provided.
5. The design shall comply with the measurement capabilities and requirements, including the ability to measure
   (a) the mass flow rate, and
   (b) the thermodynamic conditions (static and total) at the inlet and outlet of every turbine stage during the development.

#### 6.6.10.2.4 Functional: characteristic field

The characteristic field defines the turbine parameters (power or torque) for the whole region enclosed by the extreme envelope in relation to

- mass flow rate,
- pressure ratio,
- inlet temperature, and
- rotational speed.

The characteristic field can be expressed in “reduced parameters” in order to be able to use similarity rules.

Similarity rules (e.g. Mach is constant) can be used to determine the turbine operational characteristics and performance.

#### 6.6.10.2.5 Functional: characteristic field determination

a. The turbine operational characteristics and performance shall be determined for the extreme envelope.

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

c. The transient analysis for the turbine characteristics shall be performed and reported in accordance with Annex I.

6.6.10.2.6 Functional: identification of functional limits

a. The limiting parameters on the rotational speed, power, mass flow rate, operational temperatures and pressure shall be identified.

b. The limits corresponding to the parameters specified in a. should be assessed.

c. If b. is not carried out, justification shall be provided.

6.6.10.2.7 Fluid dynamic design and analysis

a. The width of the blades shall be determined by mechanical analysis, taking into account fluid dynamic and inertial loads.

b. The number of rotor blades shall be determined for a given width by fluid dynamic analysis.

NOTE The number of stator blades is determined by the vibration characteristics of the turbine stage (avoid resonance on blades).

c. The number of rotor and stator blades shall not lead to resonance within the extreme envelope (e.g. a usual design is to avoid a common divisor for the number of rotor and stator blades).

d. The blade profile shall be selected in accordance with the fluid dynamic conditions in the operating point:

1. subsonic,
2. transonic,
3. supersonic.

e. The blade profile should be selected so as to avoid flow separation.

f. If e. is not met, justification shall be provided.

g. 2-D CFD calculations, taking into account boundary layers, should be performed to investigate the flow over the blade profile for the extreme envelope.

h. A 3-D Navier-Stokes analysis should be carried out for every turbine stage to verify the fluid dynamic design for the nominal point.

i. A CFD-analysis should be carried out for the inlet flow passages and outlet flow passages for the nominal point.

j. An overall analysis shall be made to verify the following:

1. the consistency of calculations specified in g. to i.;
2. the consistency with the thermodynamic design;
3. whether the operating requirements are met.

k. A CFD-unsteady analysis should be carried out to assess unsteady fluid dynamic forces on the blades and disk.

l. Flutter characteristics of the combined blade-disk system shall be analysed.

6.6.10.2.8 Internal flows along disks and rotors

a. The various leak paths shall be determined.

b. The amount of leakage shall be assessed.

c. A flow analysis shall be made for the leakage flow through the turbine.

d. The pressure and temperature distribution on the turbine disks shall be assessed from the analysis specified in c.

e. The contribution to the axial force shall be determined from the pressure distribution determined in d.

f. A thermal analysis of the disks, rotors and stators shall be made, accounting for the following:

1. the thermal effects from the hot gas flow through the rotors and stators;
2. the flow of leakage gases.

g. The thermal analysis, as specified in f. shall be reported in accordance with Annex E.

6.6.10.2.9 Turbine mechanical design

a. General

The structural design shall be in accordance with a standard conforming to 4.2.e.

NOTE 1 For the structural design, see ECSS-E-30 Part 2A, subclauses 4.1 through 4.6.

NOTE 2 Additional factors of safety for components and subsystems that undergo ground tests can be introduced.

b. Blade attachment

1. If separate blades are used, the contact conditions between blade and disk shall be defined precisely (see also tribology).

NOTE 1 There are two rotor concepts:

- a rotor with separate blades mechanically attached,
- a rotor where the blades are an integral part of the rotor (blisk).

NOTE 2 Uncertainty about the contact surfaces can introduce serious discrepancies between the predicted and observed resonance modes and frequencies.

2. A low cycle fatigue analysis shall be made for rotors and stators experiencing hot gas flows.

c. Disk-shaft

For a mechanical connection between the shaft and the disk, it shall be assured that the connection is effective during the whole mission life (e.g. transients with thermal expansion or contraction).

NOTE The disk can be an integral part of the shaft, it can be welded to the shaft, or there can be a mechanical connection.

d. Stator

In the stator design, it shall be ensured that deformations under load, thermal expansion and contraction, and the resulting clearance between stator and rotor conform to the subsystem requirements.

6.6.10.2.10 Thermo-mechanical analysis

a. Static analysis

1. For the static analysis, the loads resulting from the worst time-consistent combination of the following shall be taken into account:
   (a) centrifugal forces (rotating parts),
   (b) pressure force (including gas bending force),
   (c) thermal loads,
   (d) interface loads, and
   (e) acceleration loads (e.g. trajectory, gimbaling).
2. Areas of stress concentrations shall be analysed, in view of fatigue.

b. Dynamic analysis

1. The eigenmodes of blades and disks shall be determined for the extreme envelope, taking into account the time-consistent combinations of steady state or transient thermal loads and centrifugal forces.
2. It shall be assured that there is no detrimental resonance within the corresponding range.
3. The following margins shall be established and respected:
   (a) The margin for the first blade tangential bending mode (1F), edgewise bending mode (1E) and torsional mode (1T), with respect to the first harmonic based on the number of stator blades.
   (b) The margin for the first blade tangential bending mode (1F), with respect to the second harmonic, based on the same number of stator blades.
   (c) The margin for the lowest disk nodal diameter axial vibration eigenfrequency in rotational speed with respect to the corresponding rotational frequency.
4. As a result, the disk and blade eigenfrequencies shall conform to the margins from 2., as illustrated in the Figure 9.

NOTE 1 Figure 9 is known as the Campbell diagram. In it the relevant multiple of the rotational speed (e.g. number of disk nodal diameters, $n$, or actual multiple of the number of stator vanes $k\ N_s$) are indicated by $N$.

NOTE 2 The $k^{th}$ harmonic with respect to the number of stator blades is derived from:

$$\Omega_k = k\ N_s\ \omega$$

where $\omega$ is the rotor angular velocity and $N_s$ is the number of upstream (and, if relevant, downstream) stator blades.

NOTE 3 The rotational frequency corresponding to an $n$ nodal diameter disk axial vibration mode is derived from:

$$\Omega_n = n\ \omega$$

where $\omega$ is the rotor angular velocity and $n$ is the number of disk nodal diameters.

5. The 15 % speed and 10 % frequency margins indicated in Figure 9 should be used.

c. Life analysis

1. The dynamic stresses in the disk and blades shall be estimated in the extreme envelope and for the mission, using the unsteady fluid dynamic loads and justified damping data.
2. A low cycle fatigue analysis shall be made (based on thermo-mechanical fatigue) in transient processes.
3. For the analysis specified in 2., the material characteristics corresponding to the actual material temperatures shall be taken into account.

   NOTE In combination with the high cycle fatigue analyses this enables the life analysis for the turbine to be carried out.

4. If simplified methods are used especially for low cycle fatigue, a life safety factor (based on experience, e.g. 10) shall be used, and the used method shall be justified.

   NOTE Simplified methods, especially for low cycle fatigue, can lead to misleading results.

5. A crack propagation analysis shall be carried out.

   NOTE For fracture control, see ECSS-E-30-01.

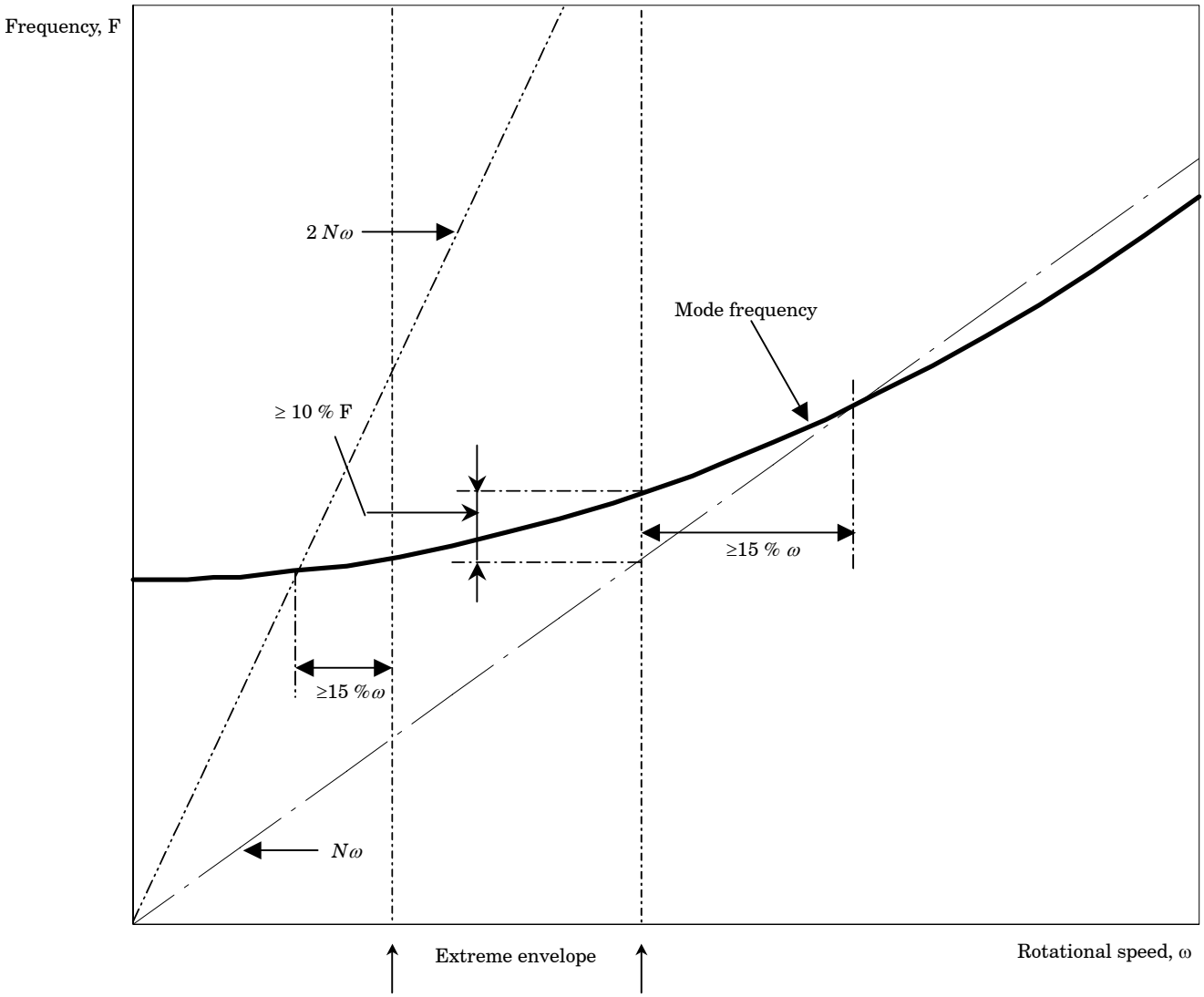



**Figure 9: Campbell diagram (in rotating frame)**

6.6.10.2.11 Materials and processes

a. The materials shall be compatible with the turbine fluids, e.g. hydrogen embrittlement, corrosion, pyrotechnic starter combustion products.

NOTE For selection of materials, see ECSS-E-30 Part 8.

b. Processes shall be selected to be in conformance with the specified material properties.

c. To reduce the residual stresses and improve the fatigue properties, highly loaded disks should receive additional treatment after machining, e.g. laser shock, shot peening.

NOTE Electro-discharge-machining and electro-chemical-machining change the properties of the material surface layer. This can affect hot parts e.g. blades and highly loaded parts.

d. If d. is not carried out, justification shall be provided.

6.6.10.2.12 Instrumentation

a. The design of the turbine shall have facility for mounting the specified instrumentation.

b. The instrumentation shall have capability for measuring parameters to verify the turbine performance and mechanical integrity (e.g. rotational speed, power, mass flow rate, pressures, temperatures, stresses, deformations and displacements).

c. It shall be ensured that during pressure measurements, the pressure is measured in a quiescent region of the flow to avoid perturbations due to blade passages.

### 6.6.10.3 Turbo pump: pump

6.6.10.3.1 Functional: overview

a. Type of pump

For rocket engines centrifugal and axial pumps are usually used. The axial pumps (e.g. inducers) are commonly used in combination with centrifugal pumps (e.g. impellers).

b. Functional – Number of stages

The number of stages is derived from

- the total pressure rise to be reached,
- the maximum pressure rise that can be obtained in every stage, and
- the level of technology and the selected materials.

An axial stage is used if the NPSP of the propellant is low and to prevent cavitation. The axial stage (inducer) precedes the centrifugal stages.

c. Characteristic curves

In the whole region of the extreme envelope the pump parameters are:

- Torque,
- Head rise ($\Delta p$).

These parameters are in relation to:

- mass flow rate
- density
- rotational speed

The pump characteristics can be expressed in reduced parameters such as (see also Figure 10):

- reduced mass flow rate: $m/(\rho\omega)$;
- reduced head rise: $\Delta p/(\rho\omega^2)$;
- reduced torque: $T/(\rho\omega)$;
- reduced NPSP: $\mathrm{NPSP}/(\rho\omega^2)$.

The effect of density and rotational speed are taken into account in these reduced parameters. Similarity rules can be used to determine pump operational characteristics and performances.

6.6.10.3.2 Functional: provisions

a. Compressibility effects shall be analysed, and the results of such analysis applied, when using similarity rules to account for them.

NOTE Hydrogen, in particular, displays severe compressibility effects.

b. The pump operational characteristics and performances shall be determined for the extreme envelope.

c. The pump characteristics shall be determined in the transient phases (e.g. start-up, shutdown) to ensure safe operation during the transient phases.

NOTE Once NPSP = 0, i.e. the local pressure equals the vapour pressure, it is not known how much of the fluid is in the liquid phase and how much in the gas phase.

d. The analysis specified in c. shall be reported in accordance with Annex I.

6.6.10.3.3 Fluid dynamic design and analysis: performance

a. The pump performance shall conform to the turbo-pump and engine requirements for the extreme envelope.

NOTE The design of a pump is a compromise between:

- dimensions,
- rotational speeds,
- cost,
- mass,
- manufacturing constraints, and
- materials.

This affects the overall pump performance. Minimizing the mass and dimensions does not automatically lead to optimal performance.

b. The effects of recirculating flows shall be taken into account in the performance analysis.

6.6.10.3.4 Fluid dynamic design and analysis: operating range

a. For stable pump operation, the pump shall operate in the part of the performance curve that has a negative slope.

NOTE A schematic of the pump performance curve in terms of reduced mass flow rate and reduced pressure rise is given in Figure 10.

b. During the development it shall be assured that a sufficient margin between the extreme envelope and the blockage region is taken in order to accommodate the changes that can be expected during the development phase.

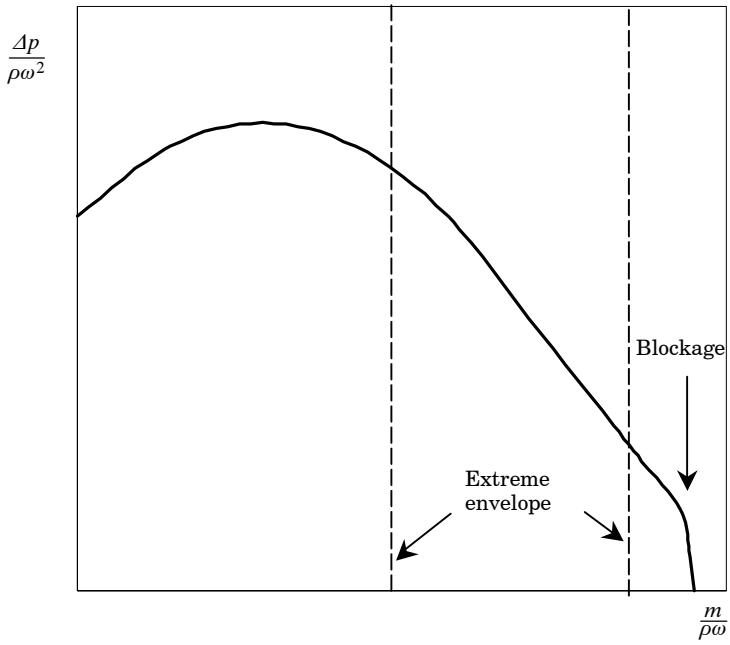



**Figure 10: Schematic of pump performance curve**

6.6.10.3.5 Fluid dynamic design and analysis: inducer-impeller design

a. General

The overall inducer-impeller design (e.g. shrouded - not shrouded, and number of blades) and the shape (e.g. backward bending, and radial or forward bending) shall take into account the following:

1. manufacturing costs and constraints,
2. performances,
3. stresses and mechanical aspects,
4. axial force control,
5. blade loads,
6. dynamic behaviour,
7. controlling of the motor.

b. Number of blades

1. The number of blades shall be based on a compromise between:
   (d) the fluid guidance,
   (e) the loads on the blades,
   (f) the reduction in flow area,
   (g) the manufacturing possibilities.

   NOTE The blades guide the fluid. However, because of their finite thickness, the blades reduce the flow of passage.
2. To improve the flow guidance, splitter blades may be installed in the downstream area of the inducer or impeller.
3. For consecutive rotating rows, without a stator in-between, the highest number of blades should be a multiple of the smallest number of blades.

c. Blade profile

1. The blade profile shall be designed such that:
   (a) the flow is attached everywhere during the nominal operational conditions;

(b) the exit flow conforms to the subsystem requirements;

(c) no boundary layer separation takes place;

(d) the wake intensity is below the specified limit.

d. The impeller shall be designed such that the static pressure, everywhere, exceeds the vapour pressure to avoid vapour formation on the blades.

e. The inducer shall be designed such that any vapour pocket that is formed is retained on the inducer and does not separate from the blade.

6.6.10.3.6 Fluid dynamic design and analysis: fluid passage

a. Recirculating flow

The design of the rotating parts and housing of the pump shall ensure that the recirculating flow is not affected by the position of the rotating part with respect to the housing of the pump.

NOTE 1 Two kinds of recirculating flows occur in pumps:

- internal leakage between rotor and housing,
- flow used at pump level to perform specific functions, e.g. cooling, lubrication and axial balancing.

NOTE 2 The internal leakage is best controlled by using a shrouded impeller.

b. Resonance coupling

To avoid resonance coupling between static and rotating parts, the following shall be taken into account:

1. Selecting a given number of rotating and static blades (e.g. with no common divisor).
2. Establishing a minimum distance between static and rotating blades to minimize pressure excitations.

6.6.10.3.7 Fluid dynamic design and analysis: cross-over

The passage of fluid from one impeller to the next one shall be designed such that:

a. flow losses do not impair the pump requirements;

b. the design conforms to the geometrical envelope;

c. the induced swirl does not impair the pump performance.

6.6.10.3.8 Fluid dynamic design and analysis: diffuser

The diffuser design shall:

a. guide the flow from the impeller into the volute;

b. ensure that pressure losses conform to the pump performance requirements.

NOTE The objective of the diffuser is to decelerate the flow and to recover the dynamic pressure. Bladed diffusers enable the pressure distribution to be smoothed in a circumferential direction, thereby reducing unsteady loads on the rotor.

6.6.10.3.9 Fluid dynamic design and analysis: volute

The volute design shall be a compromise between:

a. the overall diameter;

b. the velocity within the volute;

c. the manufacturing capabilities, cost and mass;

d. the pressure losses.

6.6.10.3.10 Fluid dynamic design and analysis: cavitation

a. The pump configuration shall be analysed for cavitation.

b. If, as a consequence of the analysis specified in a., a danger of cavitation is identified early in the design phase (project Phases A and B):

1. the inducer and impeller design shall be based on previous experience and experiments under conditions that are representative of the pump operating conditions;
2. In view of the thermodynamic characteristics of cryogenic propellants, experiments with actual propellants, under conditions that are representative of the pump operating conditions shall be performed.

NOTE 1 For the definition of the various net positive suction pressures (NPSPs) refer to 3.1.42.

NOTE 2 Meeting the $NPSP_{req}$, is essential for satisfactory pump operation which is a prerequisite for satisfactory engine operation.

NOTE 3 To maximize performance, rocket engine pumps operate in a region close to the region where severe cavitation can occur. Cavitation causes a severe performance drop (pressure, torque) and can also mechanically damage components.

c. It shall be verified by test that the inducer or impeller conforms to the suction performance requirements of the extreme envelope and functions without blockage for the whole extreme envelope.

d. The characteristics of the cavitation of the pump shall be determined in terms of pressure drop, frequencies and amplitudes.

NOTE Unsteady cavitation leads to blade vibration and radial loads on the rotating parts.

e. The acceptable level of radial loads, amplitudes and frequencies, due to cavitation shall be established, taking into account the characteristics of the bearings and the requirements on the turbo pump life.

f. It shall be verified that the pump does not exceed the limits established in e.

g. It shall be verified that cavitation does not cause secondary effects that cause malfunction of the turbo pump.

NOTE If, due to cavitation, the pressure rise in the inducer is less than envisaged this can lead to reduced coolant and lubrication flows to the bearings.

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

6.6.10.3.11 Fluid dynamic design and analysis: transfer function of the pump

a. The fluctuation in the pump outlet pressure shall be determined by fluid dynamic analysis.

NOTE Fluctuating inlet pressures to the pump have the following overall effect:

- a fluctuation in the pump outlet pressure;
- a variation in the cavitation behaviour of the inducer;
- a fluctuation in the combustion process and a subsequent fluctuation in the turbine inlet and outlet-conditions, resulting in fluctuations in the power delivered to the pump.

b. The effect of fluctuating inlet pressure on the behaviour of the inducer cavitation and subsequent fluctuations in the pump outlet pressure shall be

established experimentally in the frequency and amplitude range which is of interest for the POGO analysis for the complete range of inlet pressures and inlet temperatures.

c. The effect of fluctuating inlet pressures on the combustion and subsequent coupling with the power delivered to the pump shall be determined at the engine level.

6.6.10.3.12 Thermo-mechanical design and analysis

a. General

The structural design shall be in accordance with a standard conforming to 4.2.e.

NOTE 1 For the structural design, see ECSS-E-30 Part 2A, subClauses 4.1 through 4.6.

NOTE 2 Additional factors of safety for components and subsystems that undergo ground tests can be introduced.

b. Static analysis

1. For the static analysis, loads resulting from the worst time-consistent combinations of the following shall be taken into account:
   (a) centrifugal forces (rotating parts),
   (b) interface loads,
   (c) acceleration loads (e.g. trajectory, gimbaling),
   (d) pressure forces,
   (e) thermal loads (e.g. chill-down)
2. Areas of stress concentration shall be analysed, in view of fatigue.

c. Dynamic analysis

1. The eigenmodes of the inducer and impellers shall be determined in the extreme envelope.
2. The effect of fluid mass on the eigenmodes shall be taken into account.

   NOTE This is especially important in the case of high density fluids.
3. No detrimental resonance shall occur within the corresponding stationary domain.
4. The pump eigenfrequencies shall consequently conform to the same specified speed (i.e. ≥ 15 %) and frequency (i.e. ≥ 10 %) margins as indicated in the Campbell diagram (see Figure 9 and sub-clause 6.6.10.2.10).
5. The dynamic stresses in the inducer and impellers shall be estimated in the extreme envelope and for the mission using unsteady fluid dynamic loads, and realistic mechanical damping data.

d. Life analysis

1. A high cycle fatigue analysis shall be made for the inducer blades.
2. Based on stress levels, the need for a low cycle fatigue analysis for the impellers shall be assessed.

   NOTE For cryogenic hydrogen impellers, the result of this assessment is usually positive.
3. If simplified methods are used a life safety factor (based on experience, e.g. 10) shall be used.

   NOTE This is especially important for low cycle fatigue.
4. The life analysis shall be based on high and low-cycle fatigue analyses.
5. A crack propagation and damage tolerance analysis shall be made.

NOTE For fracture control, see ECSS-E-30-01.

6.6.10.3.13 Materials and processes

a. The materials shall be compatible with the fluids to be pumped (e.g. hydrogen embrittlement, LOx compatibility, and NTO compatibility).

NOTE For selection of materials see ECSS-E-30 Part 8.

b. Processes shall be selected that correspond to the specified material properties.

6.6.10.3.14 Instrumentation

a. The pump shall have capacity for mounting the specified instrumentation.

NOTE The instrumentation requirements depend on the program phase (e.g. development, qualification, or flight).

b. During the development phase (phase C), the instrumentation shall have the capability for:

1. the measurement of those parameters for verifying the pump performance, behaviour, and
2. failure detection and analysis (e.g. pressure, rotational speed, mass flow rate, inlet and outlet temperatures, stresses, deformations and displacements).

c. For operational engines the instrumentation should have the capabilities for

1. post flight analysis,
2. health analysis, and
3. maintenance.

NOTE The latter is especially important for reusable engines.

d. The static pressure shall be measured in quiescent regions of the flow, to avoid misinterpretation due to fluctuations.

### 6.6.10.4 Turbo pump: rotor assembly

6.6.10.4.1 Overview

There are basically two different rotor layouts:

a. All components are mounted on a shaft; the shaft can be divided in two parts which are connected.

b. The components are connected to each other by means of tie-bolts.

The main parameters that determine the layout are:

- the ability to transmit torques,
- stiffness, and
- the ability to mount components.

6.6.10.4.2 Stack-up and centring

a. It shall be assured that during the whole operational life the centring of, and the connection between, the components is maintained.

b. The effects of thermal and mechanical loads shall be taken into account.

c. The effect of the combination of the individual tolerances of the components of the rotor assembly shall be taken into account to ensure that the stack-up and centring conform to the system and subsystem requirements.

6.6.10.4.3 Rotor dynamics

a. The eigenfrequencies for the rotor assembly should conform to the Campbell diagram (see Figure 9 and 6.6.10.2.10) with the exception that a critical speed

margin higher than or equal to 20 %, and a critical frequency margin higher than or equal to 10 %, within the extreme steady state range, should be used.

NOTE See also subclause 6.6.10.1.1.

b. If the operational point lies above critical speeds of the rotor assembly, it shall be assured that during transient operations (e.g. start-up and shutdown) the critical speeds are passed fast enough so that no rubbing occurs between the rotor and stator.

c. It shall be assured that damping is sufficient to pass the critical speeds safely.

d. The rotor assembly shall be balanced, statically and dynamically.

#### 6.6.10.4.4 Materials and processes

a. The materials shall be compatible with the fluids that come into contact with them.

NOTE For selection of materials see ECSS-E-30 Part 8.

b. For the rotor assembly, a fracture control plan shall be implemented.

NOTE For fracture control, see ECSS-E-30-01.

c. The rotor shall be spin tested.

NOTE For spin testing, see ECSS-E-30-01A subclause 8.4 and subclauses 11.1 and 11.2 e.

d. An analytical verification and analysis of welded connections shall be performed.

NOTE For welding verification and analysis, see ECSS-E-30 Part 2A, subclause 4.7.16 and ECSS-E-30-01A subclauses 8.2 a, b, and c. with the exception of b2.

e. Bolted connections shall be analysed.

NOTE See ECSS-E-30A Part 2A subclause 4.7.15.

f. Connections in the rotor assembly others than specified in d. and e. shall be analysed according to recognized standards and procedures conforming to 4.2.e.

#### 6.6.10.4.5 Instrumentation (development tests)

a. The rotor assembly and housing shall have capacity for instruments to measure

1. axial and radial displacements,
2. vibrations (frequencies and amplitudes), and
3. rotational speed.

b. Radial displacements shall be measured at those locations where the maximum radial displacement can be expected.

NOTE 1 Measurements of displacements are useful to verify the proper functioning of the rotational equipment and to understand failure causes.

NOTE 2 Measurements of vibrations enable health monitoring (e.g. blade rupture and imbalance).

c. The following shall be established:

1. The locations that are critical with respect to actual displacements (e.g. gaps).
2. The information to be provided.

EXAMPLE For an active axial balancing system, this information is the gap that calibrates the flow. For an axial thrust bearing, it is the gap between static and rotating part of the bearing.

3. The locations that enable to provide the information specified in 2.

d. Axial displacements shall be measured at the locations identified in c.1. and c.3.

6.6.10.4.6 Turbo pump housing: overview

The housing has four primary functions:

1. connection to other subsystems or systems,
2. containment of the fluids,
3. to provide paths for fluid flow (e.g. cross-over, volute),
4. mechanical support for the rotor assembly, bearings and seals.

6.6.10.4.7 Turbo-pump: design

a. Architecture

1. In designing the architecture of the housing, the following shall be taking into account, as a minimum:
   (a) stiffness,
   (b) thermal behaviour,
   (c) the possibility to achieve leak tightness,
   (d) interfaces with other components and subsystems,
   (e) the available geometrical envelope,
   (f) the mounting and assembly of the housing,
   (g) the ease of manufacturing.

   NOTE For the design of the architecture of the housing, see ECSS-E-30 Parts 1, 2, 7, 8, ECSS-E-30-01 and ECSS-E-30-02.
2. The dimensioning of the housing shall take into account the loads due to feed lines.
3. To ensure proper functioning of the interfaces (e.g. leak tightness, deformations, and stresses) the interfaces shall be analysed for the expected loads (i.e. forces, thermal, and vibrations).
4. The loads on the interfaces shall be defined early in any development program (phase A and B).

   NOTE The interface loads strongly affect the layout of the turbo pump housing and the overall design.
5. The support of the housing should be in a stiff region and close to the bearings.

b. Stack-up

1. It shall be ensured that during the whole operational life the centring and alignment of the components and the connections between the components is maintained.
2. Effects of thermal and mechanical loads shall be taken into account.
3. The effect of the combination of the individual tolerances of the various components of the housing assembly shall be taken into account to ensure that the stack-up, centring and alignment conform to the system and subsystem requirements.

c. Leak tightness

1. The external leakage budget for the turbo pump housing shall be derived from the external leakage budget of the engine.

2. The seals and connections shall be designed such that they comply with the external leakage budget for the turbo pump housing.

   NOTE Start-up and shutdown transients often constitute the most severe conditions with respect to leak-tightness requirements.

3. Start-up and shutdown transients shall be taken into account for the design of seals and connections.
4. The analysis specified in 3. shall be reported in accordance with Annex I.

d. Materials and processes

Materials shall be compatible with the fluids they come into contact with.

NOTE 1 For selection of materials, see ECSS-E-30 Part 8 and ECSS-Q-70-36.

NOTE 2 For selection of mechanical parts, see ECSS-E-30 Part 7.

e. Instrumentation

1. The housing shall be designed such it enables the mounting of instrumentation (see subclauses 6.6.10.2.12, 6.6.10.3.14, and 6.6.10.4.5).
2. In those areas of the housing where high stresses are expected, measurements should be such that local peak stresses can be assessed.
3. If 2. is not met, justification shall be provided.

f. Thermal insulation

1. The need for a thermal insulation shall be assessed taking into account external fluxes, the turbo pump operational conditions, and heat transfer to subsystems and systems.
2. For the turbo pump the following shall be done:
   (a) a thermal analysis for every phase during its operation;
   (b) a report of the thermal analysis specified (a) in accordance with Annex E.
3. The analysis specified in 2. shall identify the dimensioning or critical thermal conditions for the turbo pump.
4. The maximum and minimum limits for the operating temperatures of the pump shall be established.
5. To establish the limits specified in 4., as a minimum, the following parameters shall be taken into account:
   (a) chemical stability of the liquid to be pumped (decomposition);
   (b) physical characteristics of the liquid to be pumped (e.g. vapour pressure, density, and freezing);
   (c) material characteristics of the pump;
   (d) cryo-pumping;
   (e) freezing of (external) moisture.
6. The minimum and maximum operating temperatures of the turbine shall be established.
7. To establish the temperatures specified in 6., the following parameters shall be taken into account:
   (a) freezing of trapped moisture in feed lines, valves, preventing the start-up of the turbine,
   (b) thermal shock,
   (c) thermal cycling,
   (d) material characteristics, and

(e) external heat fluxes.

8. The turbo pump design shall ensure that for the extreme envelope, the pump and turbine operate between the minimum and maximum temperatures limits.
9. The need for a thermal insulation (barrier) between the hot and cold parts of the turbo pump shall be analysed.
10. The need for an external insulation (thermal) of the housing shall be analysed.
11. The external insulation specified in 10. shall conform to the outgassing and flammability requirements and cleanliness.

NOTE For outgassing and flammability, see ECSS-E-30 Part 8A, subclauses 4.4.4, 4.4.6, and 4.4.8. For cleanliness, see ISO 14644-1:1999.

#### 6.6.10.4.8 Components: bearings

a. An analysis of all the phases of the mission shall be made to establish the dimensioning cases for the bearings.

NOTE 1 The bearing design and selection is determined by the mission, especially storage (e.g. stress corrosion), verifying the engine functioning at low rotational speed in dry condition, transport (e.g. shocks, and vibration), launch environment, and engine operation.

NOTE 2 The non-stationary and vibration loads (axial and radial) due to cavitation in the inducer or the pump are very difficult to predict or estimate. Nevertheless, these loads can be the largest experienced by the bearings.

b. If operation occurs between rotor critical speeds, an operation conforming to the system and subsystem requirements should be achieved by shifting the critical speed curves by proper choice, location and design of the bearings.

c. If b. is not met, justification shall be provided.

d. The rotor displacement shall never exceed the nominal clearance between the housing and the rotor.

e. Sufficient damping shall be provided by the seals (and bearings) to limit rotor displacement.

f. The bearings shall be designed and located such that the operating speed is separated from the critical speeds by (a) sufficient margins.

g. A margin higher than or equal to 20 % of the upper limit or lower limit of the rotational speed should be used (see subclause 6.6.10.4.3).

NOTE The critical speeds of the rotor can be affected by the gaps between the outer rings of the bearings and the housing.

h. Stress corrosion effects (for the inner ring) shall be taken into account when selecting the material for the inner ring.

i. The stresses due to shrinking the bearing on the rotor shall be taken into account.

j. The coolant flow during chill-down shall be analysed and dimensioned to ensure that the complete bearing is cooled to the specified temperatures, within the specified chill-down time.

k. For an active axial balancing system, the sliding capability of the rotor shall be maintained during start-up.

l. It shall be ensured (by design) that during purging after motor operation no pollution or contamination is introduced into the bearings (e.g. reversed flow) in case the engine is foreseen to be operated again.

m. The loads on and wear of the bearings shall be analysed (see a.) to ensure that the life of the bearings conforms to the system and subsystem requirements.

#### 6.6.10.4.9 Components: dynamic seals

a. Non-contact seals should be used, as they cause less problems than contact seals.

NOTE Contact seals are subject to wear, can create pollution and can suffer from vibrations.

b. An analysis of all the phases of the mission shall be made to establish the dimensioning cases for the seals.

c. If abradable seals are used, the pollution and contamination downstream of the seal shall be taken into account.

NOTE This includes ensuring that the pollution and contamination does not create problems, for example, injector clogging and leaking valves.

d. Barriers shall prevent contact between dissimilar fluids.

e. For flushing (dimensioning) the different ambient conditions shall be taken into account.

NOTE For ground tests, the ambient pressure is atmospheric; for flight conditions, the ambient pressures can range between atmospheric and vacuum.

f. The position of the flushing outlet shall not endanger the proper functioning of the engine or launcher.

NOTE For tribological aspects see subclause 6.6.10.4.14.

#### 6.6.10.4.10 Components: axial balancing system - overview

The axial balancing of the rotor has two objectives:

- To avoid contact between the rotor and the housing in unwanted places.
- To avoid axial loads on the bearings (in the case of an active axial balancing system).

A passive system is based on a bearing that can accept axial loads during the whole mission.

An active system is based on a pressure differential system that compensates all other axial forces on the rotor.

The selection of the type of system is based on the uncertainty in axial load: it is too large to be acceptable for a passive axial balancing system, an active axial balancing system is selected.

#### 6.6.10.4.11 Components: axial balancing system - design

a. An analysis of all the phases of the mission shall be made to establish the dimensioning cases for the axial balancing system.

NOTE The inaccuracy of this analysis can be rather large (in absolute values) for large or high-pressure turbo pumps.

b. The design of an active axial balancing system shall take the uncertainty in the axial loads into account.

c. The design and development of the active axial balancing system shall ensure that during engine operations (including transients, chill-down, start-up, and shutdown) the rotor can always slide freely in the housing.

d. It shall be ensured that the following parameters are within the specified limits:

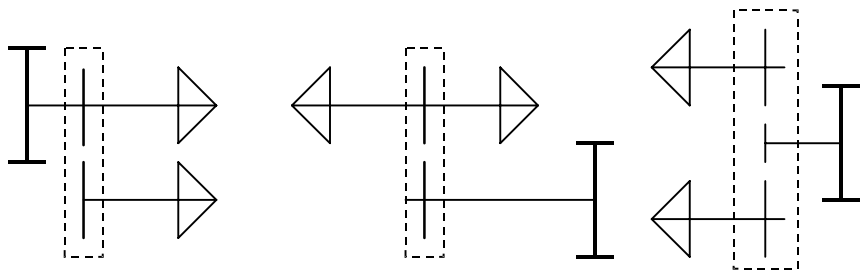
1. alignment of the housing;
2. deformation of the housing under loads;
3. thermal deformation of the housing;
4. deformation of the rotor, including bearings.

e. 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.

6.6.10.4.12 Components: gearbox - overview

A gearbox is used if the turbine rotational speed differs from the rotational speed of the pump. The gearbox enables optimization of the individual pump design and the turbine design by enabling different rotational speeds. The most common configurations are shown in the Figure 11.

The power that is transmitted by the gearbox in rocket motor turbo pumps is usually limited to less than 1 MW.



Single geared pump RL-10, HM-7 | Off-set turbine MA-5 | Pancake YLR 87

**Figure 11: Gearbox configuration**

6.6.10.4.13 Components: gearbox - design

a. General

1. To determine the need for a gearbox, a trade-off shall be made between designs using a gearbox and designs without a gearbox (see also subclause 6.6.10.1.3), taking into account the following parameters:
   (a) performance,
   (b) mass,
   (c) cost,
   (d) reliability.
2. The gearbox shall be such that:
   (a) the specified torque can be transmitted,
   (b) the specified power can be transmitted,
   (c) the turbo pump and engine life requirements can be met.
3. The gearbox shall be designed according to the recognized standards and practices, conforming to 4.2.e.

b. Lubrication and cooling

1. Lubrication and cooling of gearboxes shall be according to recognized standards and practices conforming to 4.2.e.
2. On cryogenic engines, part of the fuel may be used to cool the gearbox.
3. On non-cryogenic engines, the lubrication medium may be used for cooling (e.g. lost oil, and circulation with or without heat exchange).
4. It shall be ensured that the coolant flow maintains the temperatures of the gearbox and the gears in a range that conforms to the requirements for the clearances (see 6.6.14.2.10.d.).
5. The benefits of using "run-in" of the gearbox shall be analysed.
6. As rocket motor gearboxes have a short operational life, dry lubrication should be used.

   NOTE This is especially important for gearboxes on cryogenic engines.

c. Materials and processes

1. Materials shall be compatible with the fluids (e.g. hydrogen for cooling) they come into contact with.

   NOTE For selection of materials, see ECSS-E-30 Part 8.

2. Processes shall be selected to be in accordance with the specified material properties.

d. Instrumentation

The gearbox shall be designed such that it enables mounting of instrumentation according to the measurement plan.

NOTE See ECSS-E-10-02 and ECSS-E-10-03.

#### 6.6.10.4.14 Tribological aspects and contact

a. Table 5 and the methods to prevent the failures stated therein shall be taken into account in the tribological design.

   NOTE Table 5 lists the failure modes, the results of failure and methods to prevent failures for contacts between parts of the turbo machinery. The table is not exhaustive.

b. The methods indicated in Table 6 shall be taken into account in the design.

   NOTE With these methods, the problems described in Table 6 can be eliminated or reduced to acceptable levels. Table 6 identifies turbo pump components where (high velocity) contacts occur. These (high velocity) contacts can cause the problems identified in the table. The table is not exhaustive.

c. A FMECA of the turbo pump shall be carried out, from which the critical tribological and contact aspects shall be identified.

d. The design shall ensure that all contacts conform to the reliability and performance requirements.

**Table 5: Tribological design failure modes and prevention methods for liquid propulsion for launchers**

| Failure mode | Results of failure | Prevention methods |
|---|---|---|
| Contact welding (can occur e.g. on shrunk assemblies) | Non-destructive disassembly difficult or impossible | - Material selection<br>- Surface treatment, e.g. $MoS_2$ coating<br>- Contact pressure control (during the complete mission) |
| Fretting (can occur on e.g. blade fir trees, shaft splines, flanges) | - Particle generation (wear) resulting in:<br>- Reduced fatigue limit, leading to:<br>- Micro-cracks | - Material selection<br>- Contact pressure control (during the complete mission) |
| Galvanic corrosion | - Corroded interfaces<br>- Loss of margins<br>- Change of contact properties | - Material selection<br>- Contact pressure control (during the complete mission) |
| Stress corrosion and cracking (can occur on e.g. ball bearing inner ring, shrunk assemblies) | - Loss of integrity<br>- Loss of margins | - Material selection<br>- Appropriate stress level<br>- Quality and process control (initial oxidation level, surface roughness) |
| Rubbing (can occur on e.g. inducer-inlet housing, labyrinth seals, fluid bearings, floating rings, smooth seal, journal bearings) | - Particle generation<br>- Local hot spots causing fire or explosion | - Avoid contact by design (stack-up analysis)<br>- Assure heat dissipation by high conductivity (e.g. silver) liner (avoid hot spots and resulting hazards) and reduce friction by lubrication<br>- Use abradable materials |

**Table 6: Turbo pump components and potential problems**

| Component | Potential problems | Measures to be implemented |
|---|---|---|
| Mechanical bearings:<br>- Ball bearing (ball-ring, ball-cage)<br>- Thrust bearing | - Wear<br>- Flaking (or chafing) of the rings<br>- Cage failure<br>- Ball failure | - Design analysis<br>- Material, process and surface treatment selection<br>- Development tests<br>- Quality and process control<br>- Mounting procedures |
| Fluid bearing | - Contacts during transient phase<br>- Rubbing<br>- Transport phase | - No measures identified as yet<br>- Design analysis<br>- Material, process and surface treatment selection<br>- Development tests<br>- Quality and process control<br>- Mounting procedures |
| Face seals | - Sticking (during storage)<br>- Wear (operational phase) | - Design analysis<br>- Material, process and surface treatment selection<br>- Development tests<br>- Quality and process control<br>- Mounting procedures |
| Segmented seals | - Wear | - Design analysis<br>- Material, process and surface treatment selection<br>- Development tests<br>- Quality and process control<br>- Mounting procedures |

#### 6.6.10.5 Boost pump

##### 6.6.10.5.1 Objective

Whether or not to have boost pumps is a system or design decision (see also subclause 6.6.10.1.2).

The objective of the boost pump is to transform a propellant close to boiling or even containing a vapour phase into a propellant complying with the requirements for the inlet conditions of the turbo pump. This applies specifically to upper stages, including the chill-down.

The design of the turbo pump is strongly linked to the presence of a boost pump. A boost pump leads to a greater flexibility in the design of the turbo pump. This is especially important for large, first stage engines.

The use of a boost pump can enable lower tank pressures which can affect the tank structural mass and the design of the tank pressurization system.

##### 6.6.10.5.2 Location

A trade-off shall be made to determine the best location of the boost pump (e.g. in the sump of the tank or close to the turbo pump), taking into account:

a. pressure losses in the lines,

b. hydraulic pressure, and

c. the level of tank pressurization that satisfies the engine inlet conditions.

#### 6.6.10.5.3 Power source: overview

The engine driving the boost pump can be placed in the propellant or outside the propellant.

The boost pump can be driven by:

- electric motors, where the electrical power is supplied by the stage;
- hydraulic turbines, where the driving fluid can be high pressure propellant from the main engine;
- pneumatic turbines, where the driving fluid can be, for example, a high pressure propellant from the main engine, high pressure gas stored in tanks or turbine exhaust gases;
- mechanical means, in which case the boost pump can be driven by the turbo pump, This solution usually leads to the use of a gear box between the boost pump and the turbo pump.

If the power supply of the boost pump is provided by the main engine, an auxiliary power supply can be provided to start up the boost pump.

#### 6.6.10.5.4 Power source: design

If the engine driving the boost pump is immersed in the propellant, it shall be ensured that:

a. If a mechanical drive is used:
   1. It does not lead to leakage and sealing that do not conform to the subsystem requirements.
   2. The driving mechanism is not located outside the fluid.

b. If driving fluids with different characteristics are used, any contact between the boost pump fluid and the driving fluid is prevented.

#### 6.6.10.5.5 Pump

Boost pumps are usually axial flow type pumps (sometimes with a small radial flow component) providing a relatively small pressure rise (e.g. $\Delta p < 0{,}3$ MPa).

The boost pump can operate in a wide range of rotational speeds.

Subclauses 6.6.10.3.1, 6.6.10.3.3, 6.6.10.3.12, 6.6.10.3.13, 6.6.10.4.8, 6.6.10.4.9, 6.6.10.4.10 and 6.6.10.4.12 apply to the boost pump.

### 6.6.10.6 Power source for turbo pumps

#### 6.6.10.6.1 Overview

The pumps of liquid rocket engines are driven by turbines. The turbines are either driven solely by heated coolant gases, by gases produced by special combustors, or by hot gas tapped-off from the main chamber.

#### 6.6.10.6.2 General

The power sources shall conform to the interface requirements (i.e. functional, mechanical, electrical, and thermal) and reliability requirements (see 6.6.10.1.1).

#### 6.6.10.6.3 Expander cycle power source: overview

In the expander cycle the propellants cool the combustion chamber, the throat area and (part of) the nozzle extension. The heated propellants are fed to the turbines to provide the power to drive the pumps. The pressure drop over the turbine is limited because the propellants, after having passed through the turbines, are injected into the combustion chamber.

The options for the flow directions of the coolant are:

- co-current flow,
- counter current flow, and
- a combination of both.

6.6.10.6.4 Expander cycle power source: design

a. The cooling jacket layout may be:
   - a single cooling jacket, or
   - a cooling jacket split into multiple sections (e.g. combustion chamber, throat area, and nozzle extension).

b. The options described in a. shall be analysed, taking into account the following derived requirements and constraints:
   1. the enthalpy rise in the coolant jacket, $m\ \Delta h$;
   2. the upper limit of the drop in total pressure, $\Delta p_t$;
   3. the upper limit of the wall temperature;
   4. the manufacturing constraints;
   5. the reliability requirements;
   6. costs.

6.6.10.6.5 Bleed cycle power source: overview

The bleed cycle resembles the expander cycle, but only a part of the coolant mass flow rate is passed through the turbines and after that, dumped into the ambient or re-injected in a low-pressure section of the nozzle. This enables a much larger pressure drop over the turbines. For this reason the bleed cycle is somewhat less sensitive to variations in pressure losses over the coolant jacket.

6.6.10.6.6 Bleed cycle power source: design

a. For the bleed cycle, 6.6.10.6.4.a. shall be applied.

b. Options specified in a. shall be analysed.

   NOTE If sufficient heat cannot be extracted from the coolant jacket to power the expander or bleed cycle, an additional heat exchanger can be added.

c. The impacts of the need to test the TCA at sea level conditions shall be analysed.

   NOTE An additional constraint can be the possibility for testing the TCA at sea level conditions, in which case the regenerative cooling of the nozzle extension is limited.

6.6.10.6.7 Tap-off cycle power source: overview

The tap-off cycle takes hot, high pressure gas from the prime combustion chamber to drive the turbines. After having passed through the turbines, the gases are either dumped into the ambient, or re-injected into the nozzle at a point where the total pressures match.

Tapping off gases from the combustion chamber affects the boundary layer and the flow in the combustion chamber.

Without special provisions, the hot tap-off gases can impose severe loads on the turbine.

6.6.10.6.8 Tap-off cycle power source: design

a. The severe loads on the turbine that can be imposed by the hot tap-off gases shall be analysed.

b. The effect on wall cooling shall be analysed.

6.6.10.6.9 Staged combustion and gas generator cycle power source: overview

The staged combustion cycle uses pre-burners operating at a pressure well above the chamber pressure. The pre-burners use propellants in a mixture ratio different from the main chamber mixture ratio to reduce the combustion temperature to a value that is acceptable for the turbines. The pre-burner combustion gases drive the turbines and are subsequently injected into the main chamber.

The gas generator cycle uses a gas generator where propellants are usually burned at a mixture ratio lower than the nominal mixture ratio for limiting the temperatures. The combustion gases drive the turbines and are subsequently dumped overboard or re-injected into the nozzle extension.

6.6.10.6.10 Staged combustion and gas generator cycle power source: design

a. For the pre-burner and gas generator, the following requirements apply:
   1. They shall conform to the system requirements.
   2. They shall provide a volume for efficient combustion.
   3. They shall enable the combustion gases to attain the specified temperatures and pressures.
   4. They shall sustain all applied loads.

b. The materials for the structure shall be defined.

c. The structure mass shall be determined and conform to the system and subsystem requirements.

d. The design of the pre-burner and gas generator:
   1. should prevent flow stratification,
   2. shall take into account flow stratification.

e. If d.1. is not met, justification shall be provided.

f. The structure shall enable:
   1. mounting of components,
   2. mounting of specified equipment (e.g. transducers).

g. The structure shall ensure the integrity of the pre-burner and gas generator during its mission.

h. To satisfy g., the following parameters shall be taken into account:
   1. its life and cycles,
   2. operating time,
   3. temperatures,
   4. pressures,
   5. material compatibility with combustion products,
   6. the selected cooling and injection process,
   7. loads.

6.6.10.6.11 Fatigue and creep

a. An analysis of the fatigue behaviour shall be carried out.

b. An analysis of the creep behaviour shall be carried out.

6.6.10.6.12 Combustion instability and hot gasses

a. For combustion instability, subclauses 6.6.9.4.2, 6.6.9.4.4 and 6.6.9.4.5 shall be applied.

b. For steady state combustion and for combustion instability, it shall be taken into account that for cryogenic engines, fuel and oxidizer are usually injected as liquids.

NOTE Hot gas lines between the pre-burners or gas generators and the turbines sometimes use joints, expansion joints and curved tubes and pipes. These can cause thermo-mechanical problems.

c. The flow and heat transfer in the connection between the pre-burners or gas generators and turbines shall be analysed.

d. The mechanical design of the connection specified in c. shall be analysed, taking into account thermo-mechanical loads.

6.6.10.6.13 Transients overview

In all cases the turbine can be started in one of the following ways:

- With a combination of the pressure in the main tanks and the chill-down gases.
- By means of a gas generator, based on solid or liquid propellants.
- With high pressure gas, stored in a separate high pressure gas bottle.
- Using an external source, either electrically or pneumatically.

For the expander, bleed and tap-off-cycles there are no special provisions for shutting down the power source for the turbo pumps as this is done automatically by shutting down the engine.

6.6.10.6.14 Transients: start-up system

a. It shall be verified that the start-up system conforms to the engine requirements (e.g. response times, available turbine power, multiple starts, lifetime, and contamination).

b. It shall be ensured that if the turbo pumps during start-up pass one or more critical speeds, the critical speeds are passed safely in conformance to the engine requirements.

c. A trade-off shall be made between the potential start-up systems taking into account

1. reliability,
2. cost, and
3. mass.

d. For hot gas start-up systems the requirements in 6.6.9.3 and 6.6.12 shall apply, with the exception of 6.6.9.3.2.c. and 6.6.9.3.2.e.

e. It shall be ensured that back-flow, contamination or particulate material from the turbine start-up system does not enter into the injector of the gas-generator or pre-burner.

f. Requirement e. shall be taken into account in establishing the start-up sequence.

g. For closed cycle systems, the start-up medium shall be compatible with the complete engine system.

6.6.10.6.15 Transients: shutdown

a. When shutting down an expander cycle engine, the coolant flow to the turbines shall be taken into account in the shutdown operation.

b. For the gas generator and staged combustion cycle, the gas generators or pre-burners shall be shut down before complete engine shutdown.

c. An oxidizer rich gas generator or pre-burner shall shut down the fuel supply before shutting down the oxidizer supply.

d. A fuel rich gas generator or pre-burner shall shut down the oxidizer supply before shutting down the fuel supply.

e. It shall be ensured that, if the turbo pumps are operating above the critical speeds, during shutdown the critical regions are passed safely so as not to damage the turbo pumps conforming to the engine requirements.

## 6.6.11 Liquid engines: control and monitoring system

### 6.6.11.1 Overview

Control systems can be passive or active.

Passive control systems comprise, for example:

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

Active control systems use monitoring devices, e.g. pressure sensor, rotational speed sensor, temperature sensor, that measure those parameters that are critical for the considered equilibrium point.

For control engineering, refer to ECSS-E-60.

### 6.6.11.2 Stability

a. A stability analysis shall be made of the equilibrium points for the operation of the liquid engine.

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

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

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

NOTE This is based on experience.

e. If d. is not met, justification shall be provided.

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

g. If the stability margins are smaller than the margins established by f., or if an equilibrium point is not stable, either:

- the engine design shall be changed to ensure that all equilibrium points are stable with stability margins equal to or larger than those established by f., or
- control systems shall be implemented on the engine which shall ensure that all equilibrium points are stable with stability margins equal to or larger than those established by f.

### 6.6.11.3 Control systems

a. The value of the critical parameters for the equilibrium points, or values derived from these (e.g. mixture ratio) shall be compared with the values specified.

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 (e.g. servo valves, and flow control devices) that reset the system parameters to their specified values.

d. An analysis shall be made to establish

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

e. Passive control devices should be used if the only requirement is to assure stable equilibrium points with sufficient stability margins, and if the rates of change outside the stability margins are small enough to ensure that the passive control system can still take corrective action.

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

1. It follows from the system requirements, e.g. 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 (e.g. limitation of hot gas temperatures).

g. It shall be verified that the reliability of the liquid engine with a control system is better than the reliability of the same engine without a control system.

h. It shall be verified that the engine reliability conforms to the system requirements.

NOTE This can lead to the use of redundant hardware.

i. For the control system,

1. a FMECA shall be carried out, and
2. catastrophic failures shall be avoided.

NOTE For FMECA, see ECSS-Q-30-02.

j. The engine control system should be developed and qualified together with the engine.

k. If i. is not carried out, justification shall be provided.

l. The environment (e.g. temperature, vibration, shocks, humidity) in which the control equipment on the engine functions shall be determined.

m. Measures shall be taken to ensured either:

- that the the selected equipment can function according to requirements, during the whole mission, in this environment, or
- that the environment of the equipment conforms to the equipment requirements (e.g. venting, cooling, heating, and shielding from electromagnetic fields).

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

NOTE For functional transducers see 6.6.14.13.

## 6.6.12 Liquid engine: start-up and ignition system

### 6.6.12.1 Overview

The objective of the start-up and ignition system is to activate the propulsion system in a reliable and reproducible way.

### 6.6.12.2 General

a. The status of the propulsion system shall be verified according to qualified procedures before any activation takes place.

b. The verification specified in a. shall include

1. pressures in the tanks,
2. correct settling of the propellants in the tanks,
3. levels of propellants in tanks and pipes,
4. temperatures of the propellants at critical locations,
5. the position of valves, and
6. the continuity of electrical circuits.

### 6.6.12.3 Start-up and ignition sequence

#### 6.6.12.3.1 Overview

The provisions in this subclause depend strongly on the type of propulsion system (e.g. cryogenic or non-cryogenic, hypergolic or non-hypergolic propellants), the engine cycle (e.g. gas generator cycle, expander cycle, staged-combustion cycle).

#### 6.6.12.3.2 Normative provisions

a. The start-up for the propulsion system shall be established and qualified.

b. The start-up sequence shall take into account the following:

1. the pressurization of the propellant tanks,
2. the settling of the propellants in the tanks,
3. the engine cycle,
4. the stage system, especially electrical systems,
5. the performance of the OBCs,
6. the need for chill-down or not, as per 6.6.8.9.2.
7. the complete filling of lines, pumps and cooling circuits.

c. It shall be ensured that the transfer of the start-up and ignition sequence from the test facilities to the actual stage does not introduce malfunctions.

d. During the development, the start-up and ignition sequence shall be tested in the most representative condition with respect to the stage condition and operation in flight (e.g. “battleship” configuration, see subclause 6.8.3.).

NOTE In ground tests, complete simulation of flight conditions (e.g. zero-“g” conditions, vacuum environment) cannot always be achieved.

e. The start-up sequence shall conform to the subsystem and system requirements.

NOTE This is especially important for the following:

- tank pressurization (refer to 6.6.6.9);
- transients (refer to 6.6.8.9);
- igniter (refer to 6.6.9.3);
- coolant system – especially restarting hot engines (refer to 6.6.9.5);

- combustion instability overview – especially combustion instability during start-up and shut-down (refer to 6.6.9.4.2);
- power source for turbo pumps – especially transients, start-up (refer to 6.6.10.6);
- gas generator and pre-burner: igniter (refer to 6.6.14.15);
- monitoring and control system (refer to 6.6.17).

f. If a propulsion system is foreseen to be activated after a ballistic flight, a propellant settling analysis shall be made.

g. The main parameter to be obtained from the analysis specified in f. shall be the time it takes for the propellant to settle in the tank.

h. The design of the propellant supply system shall take into account the time obtained in g. with sufficient margin to ensure that the propulsion system functions according to the requirements.

## 6.6.13 Liquid engines: stage support

### 6.6.13.1 Overview

In 6.6.12.2 it is specified that the propulsion system is in its proper condition before ignition or re-ignition. As a result, 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 6.7).

### 6.6.13.2 Electrical

a. The electrical functions to be supplied for the initiation of the propulsion system and for the operation of the stage during the operation of the propulsion system (e.g. heating, valve operation, actuator operation, transducers, control system, and ignition) shall be identified.

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 b., based on experience, shall be established and specified.

d. The electrical battery system shall be designed with the margin established in c.

### 6.6.13.3 Gases

a. The heating, cooling, purging or venting operations to be performed for the initiation of the propulsion system and for the operation of the stage during the operation of the propulsion system (e.g. purging of injectors, coolant channels, pipes, lines and combustion chamber, heating or cooling of components, and the environment of the engine or propulsion system) shall be identified.

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

c. Based on a. and b., 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, based on experience, shall be established in order to guarantee that the operations identified in a. can be performed.

e. The gas supply system for stage support shall be designed with the margin established in d.

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

## 6.6.14 Components

### 6.6.14.1 General

a. Measures shall be taken to ensure that components can withstand all loads in the extreme envelope.

b. The loads specified in a. shall be defined independently of the components.

c. It shall be ensured that the components can withstand the loads at the point where the component is mounted.

d. To assure proper functioning of the components under launcher induced loads (i.e. mechanical, vibration, shock, thermal, and environment) a general load level shall be defined based on the extreme envelope.

e. The functioning of all components under the loads specified in d., and their capability to withstand these loads, shall be assured.

NOTE Specific requirements can also be applicable to any component.

f. Actual interface loads shall be taken into account.

g. If it appears that during the mission the loads on a component are higher than the load cases for which the component has been qualified, measures shall be taken to rectify this.

EXAMPLE Measures that can be taken include:

- reducing loads,
- re-designing or re-qualifying the component,
- selecting a different position for the component,
- modifying supporting interfaces.

h. Components that generate particles should have a filter at its outlets.

i. Component that are sensitive to particle contamination should have a filter at their inlets.

j. If h. or i. are not met, justification shall be provided.

k. If filters are installed, it shall be assured that the additional pressure drop (depending on the contamination level) and the dangers of freezing of the filter (especially in cryogenic systems), do not exceed the component or subsystem specification.

### 6.6.14.2 Valves

#### 6.6.14.2.1 Overview

Valves are used in a propulsion system for two reasons:

- to isolate, admit fluids or direct fluids;
- to control a fluid flow rate.

Some valves perform a combination of these functions.

Table 7 gives the common wording for valves commonly used on launcher propulsion systems.

**Table 7: Common wording for valves used on launcher propulsion systems**

| Valve name | Use |
|---|---|
| Flow control valve[a] | Control (propellant) flow. |
| Shut-off valve | Stop or admit any fluid according to a specified valve response and manoeuvring time.<br>Isolate fluid. |
| Isolation valve | Isolate or admit any fluid. |
| Check valve (non-return valve) | Prevent any flow back of fluid. |
| Pilot valve | To control pneumatic or hydraulic actuators. |
| Relief valve | Relieve over pressure of any fluid. |
| Servo valve | Tune control-flow towards different parts. |
| Fill-and-drain valve | Fill or empty tanks. |
| Purge valve | Admit a fluid into, or out of (parts of) the propulsion system (this can include chill-down). |
| Feed valve | Isolation valve for propellant tanks. |

a The flow control valves determines the engine operating conditions: mixture ratio, mass flow rate and pressure.

#### 6.6.14.2.2 Fluid conditions

The valve selection or valve specification shall take into account:

a. the type of fluid,

b. the pressure range (upstream and downstream of the valve), and

c. the temperature range of the fluid.

#### 6.6.14.2.3 Mass flow rate and pressure drop

The valve shall conform to the requirements for mass flow rate and pressure drop for the extreme envelope.

NOTE Mass flow rate and pressure drop over a valve are related by a pressure drop coefficient, e.g. $k = \rho \Delta p / S$.

#### 6.6.14.2.4 Transient operation

a. The valve shall conform to the specified pressure drop coefficient history, i.e. $k(t)$.

b. The valve shall conform to one of the following:

- The specified valve response time and specified valve manoeuvring time in the extreme envelope.
- A defined pressure drop history in filling a downstream vessel of specified volume under specified upstream conditions (temperature, pressure).

c. The power to be applied shall:

1. meet either of the requirements a. or b.,
2. be specified.

#### 6.6.14.2.5 Leak tightness

a. Internal leak tightness shall be specified for each flow path.

NOTE Internal leakage is leakage of fluid within the valve between positions upstream and downstream of the valve obturator. Internal leak tightness is particularly important for shut-off valves, check valves and relief valves.

b. Valves shall conform to the requirements for internal leak tightness (see also 6.6.4.2).

c. The valves should conform to the requirements for external leak tightness.

NOTE External leakage is the leakage of fluid from the inside of the valve to the environment.

d. If the requirements for external leak tightness cannot be met, measures shall be introduced to reduce the effects of external leak tightness. For example:

- collection of the leaked fluid, or
- using bellows within the valves.

NOTE External leakage is limited by requirements c. and d., to avoid the build-up of a hazardous amount of fluid in the environment, and malfunctioning of the system (see also subclause 6.6.4.2).

#### 6.6.14.2.6 Power source for valve activation

The valve shall be able to operate in conformance to the requirements for the extreme envelope and the corresponding (specified) power supply conditions:

a. Electrical:

1. voltage range,
2. maximum power consumption.

b. Pneumatic and hydraulic:

1. pressure range,
2. temperature range,
3. pneumatic or hydraulic leakage rate.

c. Pyrotechnic:

1. the variability of the pyrotechnic charge,
2. ignition voltage,
3. current and the firing pulse to be provided (duration and amplitude).

NOTE On liquid launcher engines, the power supply for the valves is usually one of the following:

- pyrotechnic,
- pneumatic,
- hydraulic,
- electric.

For large valves, which use a lot of power, pneumatic or hydraulic activation is usually used.

The activation of the pneumatic or hydraulic valves is commonly achieved by low-power electric valves.

#### 6.6.14.2.7 Lifetime and cycles

a. The valve shall conform to the mission requirements.

b. The valve shall conform to the specified number of cycles, i.e. operating the valve between maximum and minimum opening position (except for a pyrotechnic valve that opens or closes only once).

c. The valve shall be able to perform the specified number of load cycles while maintaining its specified performance.

d. The following loads shall be taken into account:

1. pressure loads,

2. temperature loads,
3. interface loads,
4. dynamic loads (e.g. inertia, and vibration and shock).

e. The number of valve load cycles shall be determined from the mission and propulsion system requirements and take into account the development program of the propulsion system.

#### 6.6.14.2.8 Normally open, normally closed or bi-stable valves

A "normally open", "normally closed" or bi-stable valve shall be selected according to the operational and safety analyses and the 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.

#### 6.6.14.2.9 Compatibility

The valve materials shall be compatible with the fluids the valve is going to encounter during the mission and with the materials the valve or parts thereof come into contact with.

NOTE For materials, see ECSS-E-30 Part 8.

#### 6.6.14.2.10 Thermo-mechanical design

a. The valve shall be designed to withstand all loads from the extreme envelope.

b. The design shall take into account the thermal gradients and different temperatures that are imposed on the valve by the extreme envelope.

c. The effects of loads and thermal expansion or contraction on the valve shall be taken into account.

d. The design shall ensure that all clearances conform to the requirements for the extreme envelope.

e. The design shall ensure that leak-tightness is maintained for the extreme envelope.

NOTE For the structural design, see ECSS-E-30-02 and ECSS-E-30 Parts 1 and 2.

#### 6.6.14.2.11 Tribological aspects

a. The materials that are in moving contact with each other shall be selected to ensure the following:

1. The friction conforms to the requirements for the extreme envelope.
2. The particle or pollution generation conforms to the cleanliness requirements.

   NOTE For cleanliness requirements, see ISO 14644-1:1999.

3. The materials are compatible with each other under moving contact.

b. Risks of jamming shall be avoided.

c. Surface treatment or lubrication of parts shall be taken into account to reduce the friction, reduce the pollution, or particle generation.

6.6.14.2.12 Pollution

a. The valve design shall take into account potential pollution of the fluid by particles.

b. A pollution analysis shall be made according to recognized standards conforming to 4.2.e.

NOTE Examples of standards that can be used for this purpose are MIL-STD-1246 C and NAS 1638.

6.6.14.2.13 Environment

a. The valve design shall conform to the performance requirements in all natural environments in which it is expected to function with respect to:

1. temperature,
2. humidity,
3. atmospheric pollution,
4. pressure ranging from atmospheric to vacuum,
5. electromagnetic fields (e.g. thunderstorms, corona).

b. Blanketing by a neutral gas should be taken into account to reduce problems with:

1. humidity,
2. atmospheric pollution,
3. corona effects,
4. temperature.

6.6.14.2.14 Mass, envelope, interface and power consumption

The valve design shall conform to:

a. the mass requirements,

b. the geometric envelope,

c. the interface requirements, and

d. the power consumption requirements.

6.6.14.2.15 Additional functions

If specified, the valve shall enable the installation of position indicators or sensors that can be connected to the engine control system.

6.6.14.2.16 Valve characteristics

Table 8 lists some characteristics of valves used in launcher propulsion systems.

**Table 8: Launcher propulsion system valve characteristics**

| Type of valve | Δp | Tightness | Short response time capability | Tuning capability |
|---|---|---|---|---|
| Flat poppet | High | High | < 100 ms | No |
| Shaped poppet | Medium to high | High | < 100 ms | Poor |
| Sleeve valve | Medium | Medium to low | No | Good |
| Ball valve | Low | High | No | Medium |
| Butterfly valve | Medium | Low | No | Medium |
| Gate valve | Low to medium | Medium to high | < 100 ms | Medium |
| In-line poppet | medium | high | < 100 ms | poor |
| Grid valve | medium | low | no | medium |

#### 6.6.14.3 Pressure regulator

##### 6.6.14.3.1 Overview

The pressure regulator controls 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.

##### 6.6.14.3.2 Normative provisions

a. The pressure regulator shall conform to the requirements for the mass flow rate and upstream and downstream pressure for the extreme envelope.

b. The lock-up pressure, including inaccuracies and the dynamic behaviour of the pressure regulator, shall not exceed the pressure upper limit downstream of the pressure regulator.

c. The sources of inaccuracies for the mechanical pressure regulator shall be analysed, including, as a minimum,

   1. inlet conditions (pressure, temperature),
   2. mass flow rate,
   3. friction,
   4. vibrations and shocks,
   5. pressure measurement,
   6. variation in external pressure, and
   7. accelerations.

   NOTE Mechanical pressure regulators that have an absolute reference pressure are usually more accurate than those having a relative reference pressure.

d. The accuracy and reliability of the pressure regulator shall conform to the system requirements.

e. The pressure regulator should only be used between the minimum and maximum mass flow rate.

NOTE A typical pressure regulator performance is shown in Figure 12. Note that there is a certain bandwidth for the downstream pressure that depends on the upstream pressure.

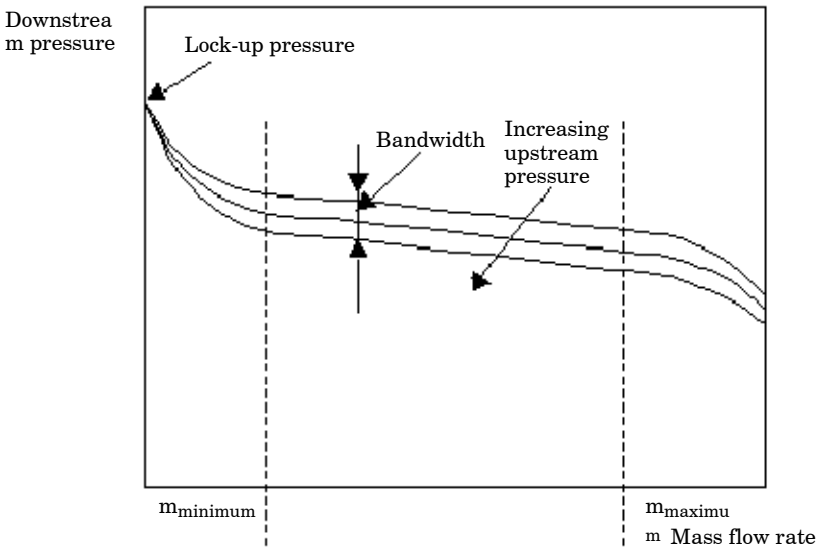



**Figure 12: Pressure regulator performance**

f. The pressure regulator shall be compatible with the fluids and the pressure and temperature range in the extreme envelope.

g. The pressure regulator shall conform to the internal and external leak tightness requirements (see subclause 6.6.4.2).

NOTE 1 The unused amount of pressurant gas strongly depends on the characteristics of the pressure regulator.

NOTE 2 Figure 13 shows characteristic curves for three mass flow rates for a mechanical pressure regulator. At low upstream pressure the differences in downstream pressures between the various flow rates increase. Vice versa, the inaccuracy of the control of the downstream pressure increases.

h. In selecting or specifying a pressure regulator it shall be taken into account that small inaccuracies in downstream pressure can be obtained only with higher upstream pressure, and therefore with a larger amount of residual pressurant gas.

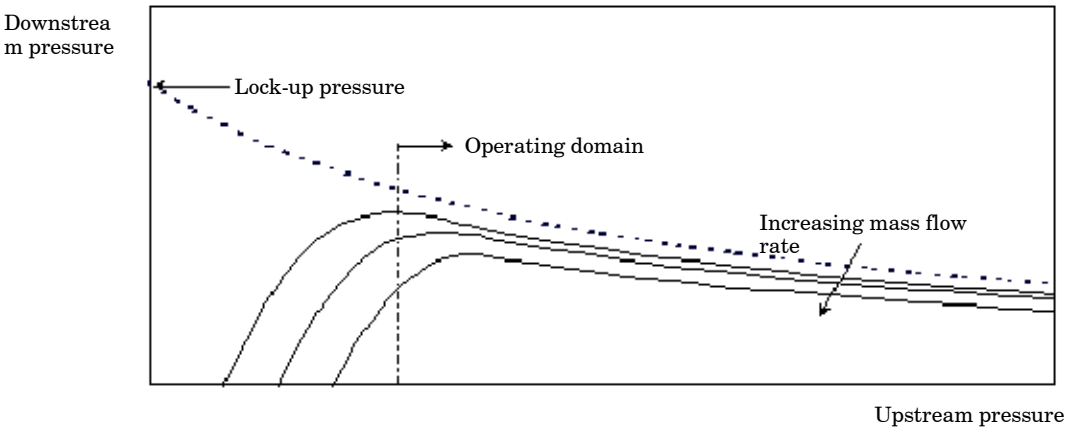



**Figure 13: Characteristic curves for pressure regulators**

6.6.14.3.3 Two-stage pressure regulator

If the requirements cannot be met with one single pressure regulator, two pressure regulators in series (two-stage pressure regulator) can be used. This can happen if the ratio of the prescribed upstream and downstream pressure is high in combination with the mass flow rate.

6.6.14.3.4 Electronic regulators

The reliability and accuracy of the electronic pressure regulator shall conform to the system requirements.

NOTE Electronic regulators measure the pressure to be regulated and activate a valve (open-close) through an electronic control circuit.

Electronic pressure regulators therefore can be adjusted by changing the settings in the control circuit.

### 6.6.14.4 Ground-board coupling devices

6.6.14.4.1 Overview

Ground-board coupling devices 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.

6.6.14.4.2 Normative provisions

a. The ground-board coupling devices for fluid connections shall conform to the requirements with respect to:
   1. mass flow rate during fluid transfer,
   2. pressure drop over the coupling device,
   3. leak tightness during fluid transfer,
   4. leak tightness after disconnecting the GSE from the launcher,
   5. the ability to decouple on command,
   6. the ability to disconnect during the launch itself (purge connections).

b. The ground-board coupling devices shall be able to withstand the thermal and mechanical loads transferred by the GSE, including atmospheric loads and decoupling forces.

c. The ground-board coupling devices shall be designed such that wrong connections are prevented.

NOTE For the electrical connections refer to ISO 15389:2001.

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

#### 6.6.14.5 Calibrating orifices

##### 6.6.14.5.1 Overview

The objective of calibrating orifices is:

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

There are two types of calibrating orifices:

1. cavitating venturi for liquids;
2. sonic orifice for gases.

##### 6.6.14.5.2 Normative provisions

a. The calibrating orifices shall conform to the requirements on mass flow rate for the extreme envelope.

b. The calibrating orifices shall be compatible with the fluids they come into contact with.

c. The accuracy, reproducibility and the stability of the flow shall be specified and verified for calibrating orifices.

#### 6.6.14.6 Filters

##### 6.6.14.6.1 Overview

The objective of filters is to retain unwanted solid particles that can be present in the flow.

##### 6.6.14.6.2 Normative provisions

a. Filters shall protect the downstream components in a fluid circuit from particulate contamination.

b. Requirement a. should be met by placing a filter directly upstream of the sensitive component or subsystem, or directly downstream of particulate generating components (e.g. pyro valves).

c. If b. is not met, justification shall be provided.

d. The decision to use, and the selection of, a type of filter shall be based on the level of internal contamination (see 6.6.4.1), the contamination tree for the propulsion system (see subclause 6.6.4.1.4), and the ability to retain particles exceeding the defined dimensions.

e. The capacity to retain particulate contamination shall be specified.

f. Filters shall be compatible with the fluids with which they come into contact.

g. Filter materials shall be compatible with each other.

h. The pressure drop introduced by the filter shall be taken into account in the fluid synopsis of the propulsion system.

NOTE The pressure drop over a filter depends on:

- the mass flow rate,
- the level of accumulated contamination in the filter,
- the size, type and characteristics of the filter.

i. The filter shall:

1. conform to the requirements for the mass flow rate and maximum pressure drop for the extreme envelope during the mission, taking into account the maximum contamination;
2. be able to withstand all loads resulting from the extreme envelope and transient operations;
3. not fail or buckle under the loads specified in 2.

#### 6.6.14.7 Gimbal joint

##### 6.6.14.7.1 Overview

The objective of the gimbal joint is that the engine can be deflected with respect to the launcher in order to perform TVC.

The gimbal joint connects the engine to the stage.

The most common gimbal joints are:

- the ball and socket gimbal joint that is used on top of the engine, and that enables deflection in two orthogonal directions;
- the cross-type joint, that also enables deflection in two orthogonal directions;
- the pivot joint, that enables deflection in only one direction.

The cross-type joint and the pivot joint can either be located on the top of the engine or at the throat region. The latter position reduces the deflection to generate the same torque and therefore reduces the envelope to be available for engine deflection.

##### 6.6.14.7.2 Normative provisions

a. The ball and socket joint shall have an additional device that prevents rotation in the third orthogonal direction.

b. The gimbal joint shall conform to the system and propulsion system requirements for the extreme envelope with regard to:

1. the maximum deflection angle;
2. the ability to transmit the thrust;
3. the ability to support the engine when it is not operating;
4. friction;
5. deformation and changes in deformation (no thrust-thrust, temperature changes and temperature gradients);
6. mechanical loads, including vibrations and shocks;
7. environment (e.g. vacuum and temperature).

NOTE For some applications the gimbal joint can only be vacuum tested at component level and not at system level. This is applies particularly to engines that do not undergo vacuum testing.

#### 6.6.14.8 Burst disk

##### 6.6.14.8.1 Overview

Burst disks are used to prevent over pressure or as an isolation device.

They are used when hermetic sealing is essential.

##### 6.6.14.8.2 Normative provisions

a. The burst disk shall be compatible with the fluids with which it comes into contact.

b. The burst pressure tolerances shall conform to the requirements for the extreme envelope.

c. The pollution generated by the burst disk shall conform to the system requirements (see subclause 6.6.4.1).

d. If the system requirements on pollution are not met, a filter shall be installed downstream to the burst disk.

#### 6.6.14.9 Piping

##### 6.6.14.9.1 Overview

Pipes and tubes are used to connect the various components in a fluid dynamic system.

##### 6.6.14.9.2 General

The pressure drop over any connection shall conform to the system requirements.

NOTE The pressure drop is reduced by using a constant cross-sectional area having a small number of turns thus assuring a smooth inner surface of the tubing and minimum length.

##### 6.6.14.9.3 Material selection

a. The material shall be compatible with the fluids with which it comes into contact during the mission.

b. The material selection shall take into account the type of connections (e.g. screw, flange, welding, and brazing).

c. The material selection shall take into account the range of temperatures during the mission.

NOTE For materials selection, refer to ECSS-E-30 Part 8 and ECSS-Q-70-36.

##### 6.6.14.9.4 Flow characteristics

a. Flow velocities in piping shall be sufficiently low that no local boiling occurs (i.e. the local static pressure shall exceed the vapour pressure, see also subclause 6.6.7.5).

NOTE High flow velocities cause larger pressure losses than small flow velocities.

b. The maximum flow velocity shall be determined as follows:

1. By performing a trade-off between pressure losses, the mass and cost of the piping and its components (e.g. valves, support fixtures, and filters).
2. By taking into account safety factors such as:
   (d) adiabatic compression (e.g. $N_2H_4$), and
   (e) risk of fire (e.g. $O_2$).

c. The flow at the pipe outlets connecting to major engine components (e.g. pumps, turbine inlets, and injector dome) shall conform to the requirements with regard to vorticity and homogeneity.

d. The line diameter shall be determined by a trade-off between

1. flow velocity,
2. pressure drop,
3. overall dimensions with respect to available space,
4. stiffness,
5. pressure thrust reaction of the bellows,
6. system dynamic considerations, and
7. cost and mass.

#### 6.6.14.9.5 Thermal insulation

a. The insulation of the piping shall ensure that the fluid conditions at the end of the piping conform to the specified limits for the whole mission.

b. For cryogenic fluids, the insulation shall ensure that no ice is formed on the outside of the piping.

c. The thermal insulation of $LH_2$ and LHe cryogenic lines shall be designed in such a way that cryo-pumping is prevented (e.g. bonding of the insulation to the piping, double insulation with ventilation).

d. The thermal insulation shall reduce the total chill-down mass consumption.

#### 6.6.14.9.6 Flexibility of piping

a. The flexibility of piping shall be such that, while keeping the corresponding interface loads within specified limits, it enables

   1. the piping to be mounted,
   2. pipes and components to be connected,
   3. misalignment,
   4. tolerances,
   5. in-service thermal and mechanical deformations, and
   6. gimbaling of the engine.

b. The changes in fluid pressure due to potential changes in piping volume shall

   1. be taken into account, and
   2. conform to the propulsion system requirements.

c. The engine feed system shall conform to the propulsion system requirements.

NOTE There are two different solutions for two degree of freedom TVC-systems:

- A direct connection such that the pipe can elongate and rotate in two directions. Such a feed line connection usually has a small pressure loss, a relatively high rigidity against gimbaling, and generally changes internal volume (unless an iso-volume bellows system has been implemented, which still increases the mass, the cost, and the rigidity against gimbaling).
- A connection such that the pipe can rotate in two planes with two angular joints (e.g. bellows with a ball-type joint). Such a feed line connection has a larger pressure loss, no changes of internal volume and a low rigidity against gimbaling.

#### 6.6.14.9.7 Elbows

a. The elbows shall be designed such that the pressure drop losses conform to the propulsion system requirements.

NOTE Elbows in piping are used to change the flow direction. This can introduce large pressure drops.

b. Elbows and other flow disturbing devices should not be placed close to the inlets of turbo pumps.

c. If components that disturb the flow are placed close to the inlets of turbo machinery, special devices should be implemented to straighten and smooth the flow.

d. If b. or c. are not met, justification shall be provided.

e. If vanes are used in the piping, it shall be ensured that the vanes do not vibrate in a frequency range outside the specified limits.

NOTE Appropriate geometry and guide vanes in angular joints can help to reduce the pressure drop and to straighten the flow.

f. The vane eigenfrequency shall be determined in the extreme envelope.

#### 6.6.14.9.8 Flexible connections: overview

Flexible connections have a low stiffness in the direction of the intended deformation.

Under pressure, the stiffness of the flexible connections usually increases.

Flexible connections are provided to enable deflection, bending, rotation, lateral translation and variation in length between connections. The main components used for flexible connections are

- the spiraled pipe,
- flexible hoses or pipes, and
- bellowed connections.

Flexible connections are commonly used to connect the engine to the stage.

#### 6.6.14.9.9 Flexible connections: fatigue life requirements

The flexible connections shall conform to the fatigue life requirements on gimbaling.

NOTE 1 The spiraled pipe is only used for small lines.

NOTE 2 Flexible hoses or pipes are only used for small and medium sized lines (∅ < ~100 mm).

NOTE 3 The flexible pipes and hoses consist of a flexible inner duct made from rubber, plastic, or corrugated metal hoses and a braided outside.

NOTE 4 The corrugated metal hoses lead to large pressure drops ($\Delta p$ ~10 × to 15 × $\Delta p$ for a smooth tube).

#### 6.6.14.9.10 Connections with bellows

a. It shall be ensured that the connections with bellows:

1. conform to the life cycle requirements for the extreme envelope;
2. can withstand the internal pressure;
3. have spring characteristics that conform to the propulsion system requirements (stiffness);
4. do not buckle under the loads and the displacements resulting from the extreme envelope;
5. conform to the requirements for pressure drop;
6. do not cause flow induced vibrations.

NOTE Connections with bellows are hermetically sealed by the bellows system and have a mechanical connection, that enable:

- angulations in any plane,
- angulations and lateral off-set,
- axial movement,
- any combination of the above.

b. The connections with bellows shall be able to satisfy the specified angular and linear deflections and elongations.

c. The design of the bellows shall be according to the recognized standards conforming to 4.2.e.

NOTE An example of a standard that can be used for this purpose is the EJMA standard.

d. For high-pressure operation, multi-ply or reinforced bellows designs should be used.

e. The dimensioning of the bellows itself shall take into account:

1. the internal pressure, and
2. the deflection or elongation.

f. The buckling stability of the bellows shall be verified under the same loads (e.g. pressure, and deformation).

g. It shall be verified that the cycles resulting from the extreme envelope do not lead to fatigue of the bellows.

h. Flow-induced vibrations within a connection with bellows shall be taken into account.

NOTE This problem can be rectified by mounting, for example, sleeves or ball-and-sockets within the bellows.

i. The ability of a connection with bellows to withstand mechanically induced vibrations shall be verified by test.

NOTE The ability of bellows to withstand mechanically induced vibrations can be improved by mounting, for example, sleeves or gimbal rings.

j. Loading connections with bellows under axial torque should be avoided.

NOTE Bellows are very sensitive to axial torque.

k. If axial torques occur, special measures shall be taken to accommodate these torques to prevent buckling.

l. It shall be ensured that the propellants and bellows materials, and the associated manufacturing processes, shall be compatible.

NOTE 1 This is particularly important for storable propellants.

NOTE 2 See ECSS E-30 Part 8 and ECSS-Q-70-36.

NOTE 3 Cleansing of bellows or connections with bellows is very difficult.

NOTE 4 Pollution, cryogenic or toxic liquids trapped in bellows can cause problems e.g. pressure excursions, and health hazards.

#### 6.6.14.9.11 Rigid connections

a. A joint of tubing or piping shall provide a leak tight mechanical connection during the whole mission.

NOTE The common connections for pipes and tubing for liquid propulsion systems are:

- flanged connections,
- screwed connections,
- welded connections,
- brazed connections.

b. When making a connection, it shall be ensured that:

1. Materials used are compatible.
2. Materials are compatible with the fluids that they come into contact with.
3. The connection processes (e.g. welding and brazing) do not introduce contamination.
4. The connection does not create contamination.

c. The design of the connection shall take into account aspects of pollution and contamination, by ensuring that:

   1. the connection is cleansed,
   2. the connection does not introduce cavities or pockets where particulate material can accumulate.

d. The margins of the performances of the selected sealing system for the extreme envelope shall be established based on experience, and specified.

e. The design of a rigid connection shall take into account the margins established by d.

f. It shall be demonstrated that the connections conform to the leak tightness requirements.

g. For flanged and screwed connections the leak tightness should be verified locally at the low pressure side of the seal during acceptance tests.

h. If g. is not carried out, justification shall be provided.

i. The design shall enable the measurements specified in g. to be performed.

j. Electrical continuity shall be ensured for bolted connections.

k. Electrical continuity shall be ensured for all connections.

   NOTE Sometimes this requirement leads to special measures, for example, in the case of anodized aluminium flanges.

#### 6.6.14.9.12 Flanged connections

a. The design of flanged connections shall into account take the following aspects:

   1. centring;
   2. the transmission of radial and torsion loads;
   3. ensuring that the bolts are only loaded within the elastic domain;
   4. the global friction coefficients and the dispersion in friction coefficients;
   5. bowing of the flanges between the bolts;
   6. locking of the bolts;
   7. electrical continuity.

   NOTE Flanged connections connect the tubes or pipes by means of flanges that are bolted together. This type of connection use specific sealing devices.

b. Lateral loads on bolts shall be avoided by the design of the connection.

   NOTE Lateral loads on bolts can stem from radial or torsion loads.

c. Centring shall be ensured by design.

d. Centring by bolts should be avoided.

e. If d. is not met, justification shall be provided.

f. The design shall take into account the deformation of the joint under combined pressure, thermal, and mechanical loads (static and dynamic).

g. The flanges at the sealing area shall be free of nicks, burrs and tool marks, except for annular tool marks.

h. The effectiveness of the sealing shall take into account the dispersion of the tightening process of the bolts, including that of related friction coefficients.

i. The pitch of the bolts shall be determined taking into account flange deformation due to bowing.

j. Measures shall be taken to ensure that the bolts are locked (e.g. wire lock, self-locking, point welding).

6.6.14.9.13 Screwed connections

a. The risk of jamming of a screwed connection shall be prevented by the selection of materials or by surface treatment.

NOTE This type of connection connects tubes or pipes by means of a nut connected to one tube which by screwing, connects to another tube. In this type of connection, a specific sealing device is sometimes used. The sealing device can be dependent on the screwing itself or independent of the screwing. The latter type includes pressure actuated seals.

Connections where one tube ends with a spherical surface and the other tube ends with a conical surface need no seals. The leak tightness depends on the force with which the two tubes are held together by the connecting nut. This type of connection can only be connected and disconnected a limited number of times. However, a conical gasket can be used to increase the number of times the connection can be connected and disconnected.

b. The margin for the leak tightness for the extreme envelope shall be established based on experience, and specified.

c. The tightening force of the nut shall be sufficient to ensure leak tightness for the extreme envelope with the margin specified in b.

d. The tightening torque and its dispersion, as well as the friction coefficient, shall be taken into account for determining the tightening force.

e. The amount of pollution or contamination generated by a screwed connection shall be determined and taken into account in the contamination tree (see 6.6.4.1).

f. The number of times a screwed connection can be connected and disconnected shall be specified and verified.

g. The number of times a screwed connection in a liquid propulsion system has been connected and disconnected shall be recorded.

h. The nut in a screwed connection shall be locked after the tightening (e.g. wire lock, self-locking, point welding).

i. Screwed and flanged connections should be located such that external leak tightness can be verified.

j. If i. is not met, justification shall be provided.

6.6.14.9.14 Welded connections

a. If it is specified that a welded connection can be dismounted and that subsequently a new welded connection can be made, the design of the welded connection shall take this into account.

NOTE Welded connections have excellent leak tightness, mechanical strength and low mass. The choice of materials for which welding can be made is limited. Dissimilar materials can be welded together; in some cases by using a transition tube.

b. The design shall take into account:

1. the material selection,
2. the welding process and the associated quality control process,
3. measures to avoid contaminating the piping.

c. As welding can affect the mechanical characteristics of some materials, reinforcement of the welded area shall be taken into account.

6.6.14.9.15 Brazed connections

The design of brazed connections shall take the occurrence of major defects into account.

NOTE The advantage of brazing over welding is the lower temperature of the process. This leads to less thermal deformation and smaller risks of affecting the material properties of the tube.

On the other hand, it is more difficult to verify the quality of brazed connections than of welded connections.

In general, welded connections are considered better than brazed connections.

6.6.14.9.16 Seals

a. The seal system shall be designed such that even under extreme transient and steady state conditions resulting from the extreme envelope, leak tightness is assured.

b. It shall be assured that, in the conditions resulting from the extreme envelope, the seal deformation is within the seal operational elastic range.

NOTE The seal can have undergone plastic deformation during mounting.

c. The mounting procedures shall take into account the characteristics of the seal and seal material.

d. Compatibility between propellants, coating materials and seal material shall be ensured.

e. Flat seals should be avoided for the following conditions:

1. pressures exceeding ~5 MPa,
2. under cryogenic conditions.

f. If e. is not met, justification shall be provided.

g. On-flight engines seals shall be replaced after disassembly.

### 6.6.14.10 Support fixtures

a. The design of support fixtures shall take into account the following:

1. static and dynamic loads due to the launcher system;
2. mechanical interface loads (static and dynamic), including gimbaling;
3. thermal loads and temperature gradients and the associated thermal expansion and contraction;
4. loads due to pressurization and the associated deformations;
5. the stiffness requirements of the component or subsystem that is held in place by the support fixture;
6. the available geometric envelope.

b. An analysis shall be made of the relative displacements between the component or subsystem and the support fixture.

c. Based on the analysis specified in b. the support fixtures shall be designed such that the subsystem or component conform to the requirements for the extreme envelope with regard to stiffness and eigenfrequencies, while the induced loads on the component or subsystem do not induce stresses that exceed the specified material stresses.

NOTE The support fixtures can provide a damping, decoupling or thermal insulation between the component or subsystem and the subsystem or system to which the support fixture is mounted.

d. For support fixtures designed to enable small rotations or displacements, it shall be ensured that no jamming or blockage occurs by
   - design,
   - material selection or surface treatment,
   - lubrication (wet or dry), or
   - a combination of the above.

e. The design of the support fixtures shall be compatible with the structure of the subsystem or system to which it is attached.

f. Electrical continuity shall be assured for the support fixtures.

#### 6.6.14.11 Heat exchangers

a. The design of the heat exchanger shall take into account the following aspects:
   1. temperature change or heat of vaporization of the fluid to be cooled, heated or evaporated;
   2. the mass flow rate of the fluid to be heated;
   3. the thermal expansion of the heat exchanger body and the heat exchanger tube;
   4. flow induced vibrations;
   5. methods to assemble the heat exchanger and the heat exchanger tube;
   6. creep at the temperature specified in the extreme envelope.

   NOTE The main function of a heat exchanger is to exchange heat between two fluids, e.g. to cool a fluid in a tank or pipe or to heat or evaporate a fluid for tank pressurization. The heat exchangers absorb heat from warm parts or warm fluids (e.g. helium to be cooled, the nozzle extension, turbine exhaust gas) and transfer this heat to the coolant fluid or the fluid to be heated or evaporated.

b. The support structure of the tube shall be designed taking into account the flow induced vibrations.

c. Materials for the heat exchanger shall be compatible with the fluids with which they come into contact at the temperatures specified in the extreme envelope.

   NOTE For materials selection, refer to ECSS-E-30 Part 8.

#### 6.6.14.12 Thermal protection

##### 6.6.14.12.1 Overview

The thermal protection is used to limit the heat flux into tanks or into sensitive equipment, components or subsystems.

For stages with storable propellants, thermal insulation is primarily used to control the propellant conditions in the tanks and lines to conform to the specified propellant conditions on ground. This thermal insulation can be jettisoned just before or during launch.

NOTE Storable propellants can reside in tanks for a long time.

Tanks can be insulated internally or externally.

Internal insulation has the following advantages:

- the insulation is protected from handling damage;
- the tank structure is isolated from the severest low temperature effects and hence is subjected to moderate thermal cycling;
- there is no local heat transfer to the propellant due to tank attachment points;

- it minimizes the propellant loss when chilling the tank during filling.

Internal insulation has the following disadvantages:

- if there is a crack or leak in a hydrogen tank, hydrogen can enter the insulation and severely impair its effectiveness;
- installation is difficult;
- locating and repairing leaks is difficult;
- cleaning the tank is difficult.

Internal insulation is primarily used for common bulkheads.

External insulation has the following advantages:

- it insulates the tank from external heating (especially severe aerodynamic heating);
- the installation, repair and sealing is relatively easy.

External insulation uses special measures for leak detection.

Cracks in the external insulation can lead to air liquefaction and cryo pumping.

For cryogenic propellant tanks, the following stages are distinguished:

- the first stage;
- stages under a fairing, or not;
- upper stages with long ballistic phases.

The most common types of thermal insulations for tanks and pipes are:

- cork, rubber, felt, fabric;
- rigid foam with closed cells (e.g. polyurethane);
- honeycomb (either filled with insulation material or not);
- layer of quiescent gas or relative vacuum;
- multi-layer insulation (MLI);
- foam with an endothermic filler.

#### 6.6.14.12.2 General

a. The thermal insulation on the propellant tanks and lines shall limit the heat flux into the tanks and lines in order to:

   1. Maintain the propellant conditions to conform to the specified conditions.

      NOTE These are derived from the engine inlet conditions.

   2. Limit the evaporation of cryogenic propellants.

      NOTE This is especially important during waiting on the launch pad.

   3. Prevent the formation of ice or frozen fluids on the outside of the tanks and lines in the case of cryogenic propellants.
   4. Conform to the thermal conditions of the interfaces.

b. The design of the thermal protection shall take into account the following aspects:

   1. the specified propellant conditions in the tank during the mission;
   2. the maximum amount of vented propellant;
   3. the maximum waiting time on the launch pad with loaded tanks;
   4. the imposed external conditions, on-ground and in-flight, that enable to assess the total heat transfer into the complete tank;
   5. the minimum external temperature of the insulation.

NOTE The heat transfer into the tanks and lines is primarily determined by convective and conductive heat transfer. In addition, hot parts (e.g. engine) and solar radiation can generate non-negligible radiative heat transfer.

c. The following shall be taken into account in the balance of enthalpy:

1. the expulsion of mass and heat from the tanks by venting propellants;
2. whether or not the tanks are pressurized by gases at a temperature different from the propellant temperature.

d. A trade-off shall be made between a disposable thermal insulation in combination with (local) insulation for in-flight conditions and an integral thermal insulation that functions on-ground and in-flight.

NOTE Trade-off parameters are:

- cost,
- mass,
- complexity.

e. For the bulkheads of the tanks:

1. the interface requirements shall be analysed;
2. the thermal protection shall be designed to conform to the interface conditions during the mission.

f. For the bulkheads adjacent to the engines, the recirculating flow in the base area shall be carefully analysed, in combination with the resulting heat transfer effects.

#### 6.6.14.12.3 Upper stages

a. Upper stages using storable propellants and experiencing long ballistic phases, shall be thermally insulated against solar radiation and cooling due to the cold space environment, to conform to the propellant requirements and conditions during the mission.

b. For upper stages not covered by a fairing, the heat transfer rate due to aerodynamic heating shall be analysed for the whole mission of the upper stage.

NOTE If a fairing covers the upper stage, the upper stage is not subjected to aerodynamic heating.

c. A heat transfer analysis for the upper stages shall be carried out, taking into account the following for the whole mission:

1. aerodynamic heating (for upper stages not covered by a fairing),
2. interface heat transfer (e.g. adjacent stage, engines),
3. conduction from attachment points and between different tanks,
4. thermal fluxes due to stage separation,
5. venting of propellant,
6. ambient heat transfer.

d. The thermal protection shall be designed such that the propellant conforms to the specified requirements for the whole mission.

e. For the upper stage the following shall be done:

1. A detailed thermal analysis, including enthalpy influx by pressurization, for the whole mission.

NOTE For upper stages with a long ballistic mission, solar radiation and conduction from other parts of the stage are major sources for heat transfer. If the duration of the ballistic phase

is very long, passive cooling by thermal insulation can be insufficient.

2. A report of the analysis specified in 1. in accordance with Annex E.

f. If the specified propellant conditions cannot be guaranteed by the design of the thermal protection, active cooling shall be taken into account.

NOTE The latter can comprise propellant evaporation and venting.

g. Rigid insulation (e.g. foam, honeycomb, cork, rubber) should be bonded to the tanks or pipes.

h. If the insulation is not bonded to the wall, the space between the insulation and the wall shall be purged by a non-liquefiable gas (e.g. He) to avoid cryo-pumping.

i. If MLI is used at cryogenic temperatures:

1. it shall either be purged by a non-liquefiable gas (He) or be placed in an environment of a non-liquefiable gas;
2. the MLI shall be pierced to allow easy outgassing during ascent;
3. for MLI the effects of changes of pressure shall be taken into account;
4. the mechanical design of the thermal insulation shall take into account the aerodynamic, static, quasi-static, dynamic and handling loads for the whole mission.

NOTE 1 MLI is specifically suited for thermal insulation under a fairing, insulation in vacuum, and as additional insulation of the bulkheads as it is not able to withstand mechanical loads very well.

NOTE 2 In many cases a combination of thermal protection materials and methods is applied.

j. The heat transfer by radiation from hot engine parts to other components or parts of the launcher shall be quantified for the mission.

k. The limit for the heat flux into the various parts and components of the launcher shall be established.

l. For those parts or components where the heat flux exceeds the limit specified in k., the following measures shall be taken to reduce the heat flux into these parts or components:

- shields that shield off the thermal radiation from the hot parts;
- wrapping the hot parts with insulating material (e.g. ceramic felt);
- insulating the part or component receiving the heat flux;
- a combination of the above.

m. If the thermal protection creates a confined volume, measures shall be taken to vent these confined volumes to avoid the build-up of hazardous gas concentrations or pressure.

n. If thermal protection is introduced to reduce emitted or received fluxes, the following apply:

1. It shall be ensured that the dimensioning cases of the affected components or parts are not be exceeded.
2. The affected parts or components need not be re-qualified.

#### 6.6.14.13 Instrumentation

##### 6.6.14.13.1 General

a. An instrumentation plan for the propulsion system shall be established, identifying the instrumentation to be used to perform the required measurements.

b. The instrumentation plan shall distinguish between the:
   1. development tests,
   2. qualification tests,
   3. normal operation of the propulsion system after the qualification.

c. The instrumentation used during the normal operation of the propulsion system shall be qualified during the propulsion system qualification phase or in a dedicated qualification programme.

d. All instrumentation shall be qualified individually according to approved standards conforming to 4.2.e.

e. All flight instrumentation shall be qualified under flight representative conditions, including the location of the instrumentation.

f. The instrumentation shall be selected according to the instrumentation plan and shall take into account the following aspects:
   1. the measurement range and performance (e.g. accuracy, response times, ageing, and stability);
   2. the fluids and materials that come into contact with the instrument;
   3. environmental constraints (e.g. pressure, acoustic noise, temperature, shocks and vibrations, fluid velocity, humidity, electromagnetic and electrostatic fields, and high energy particles);
   4. mass;
   5. geometrical envelope;
   6. interfaces (e.g. mechanical, electrical, connectors, and cables);
   7. mounting constraints;
   8. specific requirements, e.g. imposed components;
   9. calibration constraints.

g. The performance of the instruments, together with the complete measurement and data acquisition system should be verified in the laboratory, under conditions that are representative of the operational conditions.

h. If g. is not carried out, justification shall be provided.

i. Either all the functional transducers shall be exchangeable without further operation, or redundant functional transducers shall be installed.

#### 6.6.14.13.2 Mounting, location and design

a. The measurement equipment shall be mounted in such a way that it does not adversely affect the functioning of the propulsion system.

b. The instruments, together with their electrical connectors may be mounted directly on the propulsion system or on mounting plates that maintain the environmental conditions within a range that assures proper measurement conditions.

c. For the purpose specified in b. the following conditions, shall be verified as a minimum:
   1. environmental conditions (e.g. thermal fluxes, and electromagnetic conditions);
   2. the vibration and shock levels;
   3. mechanical filters that can affect the measurement accuracy (e.g. extension tubes, and pressure transducers).

d. The impact of the location and mounting on the functioning of the measurement equipment, the response and measurement accuracy should be verified.

e. If d. is not carried out, justification shall be provided.

#### 6.6.14.14 Harness

a. The harness shall conform to the interface specifications (see 6.6.16.1, 6.6.16.3.5 and 6.6.16.4.6).

NOTE The harness transmits power or information for control under the conditions of the extreme envelope and under certain specified hazardous conditions.

b. A harness plan shall be established identifying all lines of the propulsion system (e.g. electrical, and optical) to be used according to the system requirements for the following purposes:

1. measurements,
2. command, and
3. control

c. The harness plan shall distinguish between:

1. development hardware,
2. qualification hardware,
3. normal operation of the propulsion system after the qualification.

d. It shall be ensured that lines in the harness do not introduce spurious signals in adjacent or other lines (e.g. by strictly separating lines for different functions).

e. Redundant lines shall be separated physically in such a way that the redundancy is maintained (e.g. sufficient distances between redundant lines if there is the risk of fire).

f. The lines should be shielded in such a way that external perturbations do not disturb the signal in the harness lines.

g. If f. is not carried out, justification shall be provided.

h. Connectors and plugs shall be designed such that wrong connections are prevented.

i. The harness and its components shall conform to the environmental conditions (e.g. vibration level, ambient pressure, humidity, and temperature).

j. It shall be ensured that the environmental conditions are specified and accounted for in the design and manufacturing of the harness (e.g. ventilation of plugs and connectors).

k. Sensitive parts of the harness should be protected from high temperature gases or flames.

l. If k. is not carried out, justification shall be provided.

#### 6.6.14.15 Gas generator and pre-burner

##### 6.6.14.15.1 Overview

The gas generator and pre-burner produce and deliver gases in the specified conditions (e.g. temperature, and compositions) to drive the turbines.

In addition, the gas generator and pre-burner can have the following secondary functions:

- support components (e.g. igniter, turbine starter, feed valves, and heat exchangers);
- enable the installation of transducers and measurement equipment;
- provide pressurized fluids to subsystems (e.g. tank pressurization).

NOTE Sometimes gas generators are used only for tank pressurization.

The main components of the gas generator or pre-burner are:

- the injector,
- the igniter,
- the combustion chamber,
- the piping system that connects the gas-generator or pre-burner to the turbine inlet.

6.6.14.15.2 Performance

a. The level of stratification shall be verified during the development phase (phase C).

NOTE The performance of a gas generator or pre-burner is measured in

- $C^*$-efficiency,
- injector and combustion pressure loss, and
- stratification.

Stratification is the occurrence of streams of gas with different temperatures or composition. The local variation in gas temperature that the turbine stator and blades can accept is limited and usually specified by the turbine requirements. Temperature variations also reduce the gas generator or pre-burner life. For that reason, stratification is an important parameter.

b. For the $C^*$-efficiency analysis, the composition of the combustion products and the combustion temperature shall be determined using the same method as for the main combustion chamber (see 4.3.2.4, and 6.6.8.3).

NOTE Kinetic effects and incomplete combustion are more prominent for values that vary greatly from the stoichiometric mixture ratio, especially for hydrazine, hydrazine-compounds and hydrocarbon type fuels. Hydrocarbon type fuels can generate a lot of soot in fuel rich conditions.

6.6.14.15.3 Types of gas generators or pre-burners

a. A trade-off analysis shall be made, taking into account the propulsion system requirements, to determine the type of gas generator or pre-burner to be used on the engine.

NOTE Gas generators or pre-burners can use the following:

- monopropellants decomposed catalytically – used only for gas generators – need no igniter;
- bipropellant pre-burners, that are either fuel rich or oxidizer rich; a particular case is the stoichiometric gas generator where an inert fluid (e.g. water) is added to cool the combustion gases, in which case the gases can also be used for tank pressurization.

If hypergolic propellants are used, they need no igniter.

To limit the temperatures, non stoichiometric gas generators and pre-burners operate far from the stoichiometric mixture ratio. This can lead to ignition and combustion instability problems. For this reason, close to the injector the mixture ratio can be closer to the stoichiometric point while the

remainder of the propellant can be used initially for cooling and later be mixed with the combusted propellants.

b. The extreme envelope for the gas generator or pre-burner shall be determined from the engine requirements.

c. The extreme envelope determined in b. shall be used for the design of the gas generator or pre-burner, taking the stratification into account.

#### 6.6.14.15.4 Injector

For the injector subclause 6.6.9.2 applies. The injector pattern has a strong influence on the $C^*$-efficiency, the stratification and the combustion stability. The main patterns used are:

- uniform mixture ratio,
- hot core with or without subsequent dilution with the remaining propellant.

#### 6.6.14.15.5 Igniter: overview

The overview given in subclause 6.6.9.3.1 applies, with the exception that no ground torch can be used for ignition.

#### 6.6.14.15.6 Igniter: provisions

For the igniter, subclause 6.6.9.3.2 shall apply, with the exception that pre-burners may operate under oxidizer-rich mixture ratios.

#### 6.6.14.15.7 Combustion chamber

a. The combustion chamber shall:

1. provide a volume for efficient combustion of the propellants;
2. enable the combustion gases to attain the specified temperatures and pressures;
3. enable the mixing of combustion gases with diluting fluids;
4. enable the engine turbo machinery to be powered;
5. enable the specified provision of gases for tank pressurization;
6. sustain the applied loads.

b. The outside of the combustion chamber shall:

1. conform to the geometrical requirements and constraints, and
2. conform to the thermal requirements of the interfaces.

NOTE The main parameters that determine the shape of the combustion chamber are:

- the available envelope for integration of the gas generator or pre-burner on the engine;
- the minimum length to achieve good combustion efficiency, good mixing of the combustion gases and diluting fluids, reduction of the stratification to a level specified by the turbine, and the level of flow straightening specified by the turbine.

c. The internal shape of the combustion chamber shall be determined from a flow, mixing and combustion analysis (including optimization).

d. For the structure, subclauses 6.6.5 and 6.6.9.1.3 shall apply.

e. It shall be ensured that hydrogen embrittlement and fire and oxidation or corrosion in oxygen rich environments do not occur.

#### 6.6.14.15.8 Coolant system

For reasons of cost and complexity, regenerative cooling for gas generators or pre-burners should not be used.

NOTE In some types of gas generators or pre-burners, initially, a mixture ratio closer to stoichiometry is used than the overall or final mixture ratio. In this case there is usually a sleeve in the first section of the combustion chamber that is convectively cooled by the remainder of the propellants that are mixed later with the combustion gases.

#### 6.6.14.15.9 Transients

a. Subclause 6.6.8.9 shall apply.

b. Temperature overshoots or undershoots shall be controlled to avoid stresses on the gas generator or pre-burner and downstream components outside the specified limits.

c. If specified, it shall be ensured that the gas generator or pre-burner does not contain frozen or condensed combustion products, remainders of propellants or other fluids that can freeze, condense or detonate (e.g. $H_2O$, $CO_2$, and nitrates).

d. After shutdown, the gas generators or pre-burner and downstream components shall be purged.

e. It shall be verified that the gas generator or pre-burner is able to operate in combination with the turbine starter.

#### 6.6.14.15.10 Combustion instability

a. It shall be verified that the combustion instability in the gas generator or pre-burner:

   1. does not limit the life of the gas generator or pre-burner;
   2. does not adversely affect the gas generator or pre-burner performance;
   3. conforms to the system and subsystem requirements.

   NOTE 1 See also 6.6.9.4.2.

   NOTE 2 Combustion instability in gas generators or pre-burners can be related to:

   - the feed system, or
   - the combustion process.

   Instabilities often occur during transients, i.e. start-up and shut-down.

   Feed system related instabilities can arise from a coupling between the feed system and pressure fluctuations in the gas generator or pre-burner (chugging) if the injector pressure drop is smaller than the pressure fluctuations in the chamber.

   Combustion instabilities related to the combustion process are usually high frequency acoustic oscillations. They are related to the mixing and evaporation processes.

   In chambers with very small residence times, low frequency, combustion related oscillations can occur.

b. As combustion instabilities are usually linked to the acoustics of the combustion chamber:

   1. The acoustic modes in the chamber should be determined at an early stage in the design.

2. It should be ensured that the eigenfrequencies of the chamber do not coincide with other engine eigenfrequencies (e.g. feed system).
3. It shall be ensured that, even at extremely low temperatures, the delays in vaporization or heating do not create instabilities that can affect the performances (e.g. temperature of hydrogen).

NOTE This can happen if the heat of vaporization or heating of one of the propellants is much higher than for the other.

c. Combustion instability damping devices shall increase the gas generator or pre-burner stability margin by:
   1. suppressing the growth of oscillatory combustion;
   2. damping pressure oscillations;
   3. limiting the amplitude of pressure oscillations to values that conform to the engine requirements.

d. It shall be demonstrated that instrumented test gas generators or pre-burners are statically and dynamically stable as follows:
   1. under extreme pressure, temperature and mixture ratio conditions, no combustion instability occurs (static stability);
   2. the gas generator or pre-burner shall have sufficient margin conforming to the gas generator or pre-burner and (sub)system requirements (static stability);
   3. the gas generator or pre-burner shall remain stable after a perturbation, e.g. bomb testing, ramping, bubble ingestion (dynamic stability).

#### 6.6.14.15.11 Piping

For the gas generator or pre-burner, inlet and outlet piping, 6.6.14.9 applies.

### 6.6.14.16 Actuators

#### 6.6.14.16.1 Overview

Actuators are used for TVC, to drive valves for extendable nozzle cones, and for disconnecting ground-board coupling devices.

#### 6.6.14.16.2 Normative provisions

a. In selecting an actuator, a trade-off shall be made taking into account the following:
   1. the subsystem or system requirements (e.g. response time, deflection or displacement, and force or couple delivered by the actuator);
   2. the available energy and power (e.g. electrical, high pressure gas, and pyrotechnic);
   3. the transmission method (e.g. hydraulic, pneumatic, mechanical, and electromagnetic);
   4. the capability to monitor positions;
   5. maintainability;
   6. reliability;
   7. mass;
   8. cost.

NOTE Typical characteristics of some actuators used in launcher propulsion systems are summarized in Table 9:

**Table 9: Characteristics of some actuators used in launcher propulsion systems**

| Type of actuator | Advantages | Disadvantages |
|---|---|---|
| Electrical | - Control (closed loop) is simple<br>- Good maintainability<br>- Redundant electronic components easily implemented<br>- Operability simple and easy | - Limited power, i.e. limited couple or force or long operating time<br>- Development costs of electronic components are high<br>- Availability of replacement components after some years is difficult<br>- Constraints on materials (temperature dependence of material properties. e.g. magnetism) |
| Pneumatic | - Short operating time (fast action),<br>- Large forces or couples<br>- Can use gas already available on the propulsion system (e.g. $N_2$, He)<br>- Simplicity and reliability | - Closed loop control is difficult,<br>- Sensitive to leakage<br>- Dispersion in response time can occur unless special precautions are taken |
| Hydraulic | - Closed loop control easily performed<br>- Large forces or couples<br>- Short operating time (fast action) | - Operability is complex (to avoid pollution from hydraulic fluids)<br>- It implies the use of special hydraulic fluids<br>- For cryogenic propulsion systems compatibility with the environment can pose problems (e.g. viscosity or freezing of the hydraulic fluid)<br>- Sensitive to leakage, also causing pollution |
| Pyrotechnic | - Large forces or couples<br>- Short operating time (fast action)<br>- High reliability<br>- Low cost | - One shot item<br>- Special precautions to prevent inadvertent ignition<br>- For cryogenic propulsion systems compatibility with the cryogenic environment can pose problems<br>- Internal particle generation |

b. Actuators should have position indicators, either indicating the two extreme positions or providing a continuous indication.

c. To ensure a reliable position indication, the actuator should use its maximum stroke.

d. If b. and c. are not met, justification shall be provided.

e. For actuators that have a locking mechanism to hold the actuator in place, it shall be ensured that the locking mechanism conforms to the reliability requirements.

f. For electro-magnetic actuators, a margin between 20 % to 40 % on the delivered electro-magnetic force should be used.

NOTE This margin is determined by experience.

g. The delivered electro-magnetic force shall be determined for the worst-case conditions.

h. For actuators that operate continuously, as for gimbaling:

1. clearances shall be taken into account and controlled to assure accurate operation of the actuator;
2. tribological aspects shall be taken into account to avoid wear and increase of friction during the mission.

#### 6.6.14.17 POGO suppression device

##### 6.6.14.17.1 Overview

The most common POGO suppression devices damp coupled pressure and mass flow rate fluctuations in a propellant feed line. Propellant is admitted from a buffer volume into the feed line if there is a decrease in the pressure, and propellant is admitted from the feed line into the buffer if there is an increase in the pressure.

The buffer can be pressurized by a gas or by a piston system and is tuned for the expected POGO frequency range.

The following are the most common technologies for this type of POGO suppression device:

- A piston with a spring acting on the propellant thereby affecting the impedance of the feed line.
- A trapped bubble system where a gas volume acts on the propellant thereby affecting the liquid and gas volumes in the buffer. During fluctuations, propellant flows in or out of the buffer thereby suppressing pressure fluctuations, while some gas from the trapped bubble is expelled into the propellant feed line. This implies the use of a gas supply.
- A variation on the trapped bubble system is one where the gas is contained in a bellows or cylinder with piston. In this case the system needs no gas supply to the bellows or cylinder but it implies the control of the pressure in the cylinder of bellows.

##### 6.6.14.17.2 Normative provisions

a. The requirements for the POGO suppression device shall be derived from the expected pressure fluctuations and the propulsion system requirements.

b. In selecting a POGO suppression device, a trade-off between the various systems shall be made, taking into account the following (see also 6.6.7.3):

   1. the propulsion system requirements;
   2. the ability to suppress fluctuations (e.g. amplitudes, frequencies, bandwidths, and margins);
   3. the use of pressurant gas;
   4. reliability;
   5. cost;
   6. mass.

c. The following parameters that characterize a POGO suppression device, shall be taken into account for the dimensioning of such a POGO suppression device:

   1. resonance frequency;
   2. bandwidth of the resonance frequency;
   3. capacity (size).

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

e. It shall be verified that the POGO suppression device does not adversely affect the functioning of the propulsion system (e.g. gas ingestion into the feed line).

f. During stage tests, there should be verification that dynamic measurements of the pressure fluctuations are being made as specified.

g. If f. is not met, justification shall be provided.

#### 6.6.14.18 Propulsion system controller

##### 6.6.14.18.1 Overview

The propulsion system controller is a dedicated spacionics system to control the propulsion system.

##### 6.6.14.18.2 Normative provisions

a. For the propulsion system controller, 6.6.11 applies.

b. The propulsion system controller shall meet recognized standards for spacionics conforming to 4.2.e.

#### 6.6.14.19 Component failure modes

##### 6.6.14.19.1 Overview

Table 10 provides to the designers and system engineers the component failure modes typically encountered when using (standard) liquid propulsion system components.

##### 6.6.14.19.2 Normative provisions

a. Table 10 shall be taken into account during the development.

b. Depending on the criticality of the failure mode, failure detection devices should be introduced on the flight vehicle.

c. If b. is not carried out, justification shall be provided.

**Table 10: Liquid propulsion for launchers component failure modes**

| Component type | Failure mode | Failure detection | Failure prevention |
|---|---|---|---|
| Injector | Blockage of elements | - Pressure measurement<br>- Mass flow rate measurement<br>- Visual inspection<br>- Temperature measurement | - Design analysis<br>- Quality control<br>- Conformance of propellants to the specifications<br>- Temperature control of the propellants |
| | Deviation in pressure drop | - Pressure measurement<br>- Performance anomalies<br>- Flow check<br>- Vibration measurements | - Design analysis<br>- Quality and process control<br>- Dimensional control |
| | Leakage | - Pressure leakage test<br>- He-leakage test | - Design analysis<br>- Quality and process control |
| | Unsteady flow | - Post-firing inspection<br>- Vibration measurements<br>- Performance analysis | - Design analysis<br>- Quality and process control |
| | Wrong flow direction | - Temperature measurements<br>- Subsystem performance analysis<br>- Post-firing inspection | - Design analysis<br>- Quality and process control<br>- Dimensional control |
| | Overheating | - Temperature measurements<br>- Post-firing inspection | - Design analysis<br>- Quality and process control |
| | Rupture | - Proof test or NDI | - Design analysis<br>- Quality and process control |

**Table 10: Liquid propulsion for launchers component failure modes**
*(continued)*

| Component type | Failure mode | Failure detection | Failure prevention |
|---|---|---|---|
| Chamber | Rupture of liner | - Post-firing and visual inspection<br>- Pressure leak test<br>- NDI<br>- Pressure drop during test | - Design analysis<br>- Fatigue analysis<br>- Quality control<br>- Chamber polishing |
| | Rupture of welding | - Change in performance<br>- NDI<br>- Pressure leak test | - Design analysis<br>- Fatigue analysis<br>- Fracture analysis<br>- Quality and process control |
| | Blockage of coolant channels | - NDI<br>- Post-firing inspection<br>- Flow check<br>- Wire probing | - Design analysis<br>- Quality and process control<br>- Conformance of propellants to the specifications<br>- Proper maintenance of coolant channel inlet conditions |
| | Leakage | - Pressure leakage test<br>- He-leakage test<br>- Post-firing inspection | - Design analysis<br>- Quality and process control |
| | Overheating | - Temperature measurement<br>- Post-firing inspection<br>- Pressure measurement in cooling circuits | - Design analysis<br>- Material control<br>- Control of operating conditions |
| | Loss of integrity between outer shell and coolant channels | - Visual inspection<br>- Post-firing inspection<br>- NDI | - Design analysis<br>- Quality and manufacturing control |

**Table 10: Liquid propulsion for launchers component failure modes**
*(continued)*

| Component type | Failure mode | Failure detection | Failure prevention |
|---|---|---|---|
| Nozzle | Loss of integrity: cracks | Post-firing inspection | - Design analysis<br>- Quality and manufacturing control |
| | Loss of integrity: buckling (axial, radial and local) | Post-firing inspection | - Design analysis, heat transfer analysis<br>- Transient analysis<br>- Load analysis (e.g. thrust, thermal, gimbaling, side load, buffeting) |
| | Loss of integrity: rupture of welds | Post-firing inspection | - Design analysis<br>- Fracture mechanics<br>- Quality and process control |
| | Overheating | - Temperature measurement<br>- Post-firing analysis and inspection | - Design analysis<br>- Analysis of (transient) shock patterns<br>- Mixture ratio control (locally)<br>- Process control on thermal barrier coating |
| | Leakage | - Leakage pressure test<br>- Post-firing inspection | - Design analysis<br>- Quality control<br>- Seal design |
| | Blockage | - NDI<br>- Post-firing inspection<br>- Wire probing<br>- Flow check | - Design analysis<br>- Quality and process control |
| | Excessive deformation | Post-firing inspection | - Design analysis<br>- Load analysis<br>- Thermal analysis<br>- Quality and process control |
| Transducers | Zero shift, measurement anomaly | Calibration | - Incoming inspection<br>- Mounting procedures<br>- Proper accounting for specific transducer characteristics |
| | Severe damping of dynamic signals | Simulation on test item | Proper design |
| | Leakage | Leak test | - Design analysis<br>- Quality control |
| | Rupture of connections (see also 6.6.14.13) | No signal | - Mounting procedures<br>- Quality assurance<br>- Specific protection |
| | Debonding (e.g. strain gauge) | Zero shift | - Mounting procedures<br>- Quality assurance |

**Table 10: Liquid propulsion for launchers component failure modes**
*(continued)*

| Component type | Failure mode | Failure detection | Failure prevention |
|---|---|---|---|
| Gimbal joint | Blockage | Gimbal test | - Design analysis<br>- Proper mounting procedures<br>- Thermal control |
| | High friction | Gimbal test | - Design analysis<br>- Proper mounting procedures<br>- Proper lubrication<br>- Material selection<br>- Thermal control<br>- Design analysis<br>- Quality control |
| | Wrong clearances | - Assembly test<br>- Post-firing analysis | Mounting procedures |
| | Crack propagation | - Visual<br>- NDI<br>- Loss of gimbaling function | Fracture control |
| Turbo pump: turbine disk | Burst | Visual, loss of functionality | - Design, quality<br>- Process and manufacturing control<br>- Acceptance spinning test<br>- Material selection |
| | Crack propagation | Post-test inspection, imbalance, unusual deformations | - Fatigue analysis<br>- Fracture control<br>- Design against resonances<br>- Material selection<br>- Manufacturing processes minimizing residual stresses<br>- Shot peening<br>- Quality control<br>- Design |
| | Resonance | - Vibration measurements<br>- Unusual deformations | Design, damping devices (disk dampers) |
| | Flutter | - Vibration measurements<br>- Unusual deformations | |

**Table 10: Liquid propulsion for launchers component failure modes**
*(continued)*

| Component type | Failure mode | Failure detection | Failure prevention |
|---|---|---|---|
| Turbine pump: Turbine blades and blade attachments | Rupture of turbine blades | - Performance decay<br>- Vibration measurement<br>- NDI | - Modal and mechanical analysis<br>- Model test |
| | Blade resonance | - Vibration measurement<br>- Holographic measurements<br>- Post-test inspection | - Design<br>- Blade dampers |
| | Blade flutter | - Vibration measurement<br>- Post-test inspection | - Design<br>- Blade dampers |
| | Crack propagation | - NDI<br>- Visual<br>- Frequency shifts | - Design<br>- Fracture control<br>- Quality control |
| | High and low cycle fatigue (blade attachment, lower part airfoil) | Post-test inspection | - Design<br>- Material selection<br>- Material coating (fir tree attachment)<br>- Shot peening<br>- Blade dampers |
| | Fretting | Post-test inspection | - Material selection<br>- Design<br>- Surface treatment<br>- Coating<br>- Shot peening<br>- Foil insert |
| Turbo pump: stator vanes | Blade resonance | Vibration measurement | Design |
| | Rupture of blades (High and low cycle fatigue; crack propagation) | - Performance decay<br>- Post-test inspection | - Design, material selection<br>- Fatigue analysis<br>- Fracture control |
| Turbo pump: turbine housing | Lack of stiffness | - Performance analysis<br>- Too low critical speeds | Design |
| | Crack propagation | - Visual inspection<br>- NDI | - Material and process selection<br>- Quality control<br>- Design (avoid stress concentrations)<br>- Fracture control |
| Turbo pump: turbine manifold | Low cycle fatigue and crack propagation (including leakage), burst | - Visual inspection<br>- NDI<br>- Performance loss | - Design<br>- Material selection<br>- Fracture control<br>- Burst and proof test<br>- Quality control<br>- Welding processes |
| Turbo pump: inducer | Inducer (blade) failure | - Vibration measurements<br>- Performance decay<br>- NDI | - Design<br>- Modal and mechanical analysis Cavitation dynamic load assessment |
| Turbo pump: impeller | Crack propagation, burst | - Vibration measurement<br>- NDI | - Design<br>- Material selection<br>- Fracture control<br>- Burst and acceptance spin tests Quality control |

**Table 10: Liquid propulsion for launchers component failure modes**
*(continued)*

| Component type | Failure mode | Failure detection | Failure prevention |
|---|---|---|---|
| Turbo pump: cross-over diffuser | Excessive deformation, crack propagation | - NDI<br>- Performance decay | - Design, material selection<br>- Fracture control<br>- Burst and acceptance pressure tests<br>- Quality control |
| Turbo pump: rotor assembly | Rotor over speed | - Rotor speed measurement<br>- Performance measurement | - Control of inlet pressure<br>- Engine switch-off on red-line for rotational speed<br>- Correct chill-down<br>- Correct propellant inlet conditions |
| Turbo pump: axial balancing system | Spool rubbing, excessive axial loads on bearings | - Axial displacement<br>- Bearing temperature<br>- NDI | Correct design (axial load prediction) and cooling |
| Turbo pump: dynamic seals | Failure of the barrier between dissimilar fluids | - Barrier gas feed pressure anomaly<br>- Drain pressure measurement<br>- Post-firing leakage test | - Thermo mechanical analysis<br>- Quality and process control<br>- Avoidance of large pressure differences over the barrier<br>- Correct chill-down |
| Turbo pump: housing and volute | Leakage of housing | - Gas concentration measurement<br>- Performance decay<br>- Post-firing leakage test<br>- NDI | - Design analysis<br>- Quality and process control<br>- Mounting procedures<br>- Fracture control |
| Turbo pump: bearings | Bearing degradation | - Bearing temperature measurement<br>- Vibration measurement<br>- Sliding capability of rotor (for active balancing system) | - Design analysis (especially radial loads)<br>- Quality and process control<br>- Mounting procedures |
| Turbo pump: turbo pump assembly | Unwanted high-speed contact between rotating and static parts | - Post-firing inspection<br>- Vibration measurements<br>- Displacements<br>- Performance measurements<br>- Acoustic measurements | - Design analysis<br>- Rotor dynamics analysis<br>- Stack-up analysis<br>- Quality and process control<br>- Load assessment<br>- Mounting procedures<br>- Material selection<br>- Engine switch-off, or turbo pump speed reduction on red-line on control parameters |
| | Rotor blockage | - No starting of engine<br>- Rotor torque too high (out of specification) | - Control of propellant inlet conditions (chill-down, temperature, cleanliness, pressure)<br>- Conditioning of the turbo pump<br>- Quality and process control<br>- Design analysis (including pollution, moisture) |
| Turbo pump: gear box | Gear teeth wear and rupture, blockage | - Loss of performance<br>- NDI | - Design, stack-up and clearance analysis<br>- Material and processes<br>- Tribology<br>- Lubrication<br>- Quality control |

**Table 10: Liquid propulsion for launchers component failure modes**
*(continued)*

| Component type | Failure mode | Failure detection | Failure prevention |
|---|---|---|---|
| Valve: general | No switching to open or close | - Pressure measurement<br>- Performance deviation<br>- Position indicator | - Design analysis<br>- Quality control<br>- Conformance to propellant specifications<br>- Redundant actuator<br>- Thermal differential analysis<br>- Margin analysis<br>- Humidity control (cryogenic valves) |
| | Internal leakage | - Pressure measurement<br>- History<br>- "Sniffing"<br>- Performance deviation | - Design analysis<br>- Quality control<br>- Filters<br>- Cleanliness<br>- Materials control<br>- Storage conditions and ageing control |
| | External leakage | - "Sniffing"<br>- Visual inspection<br>- Pressure measurement<br>- Performance deviation<br>- NDI with bubble forming fluid<br>- Mass spectrometry | - Design<br>- Quality and process control<br>- Material selection |
| | Un-commanded valve actuation | - Pressure measurement<br>- Valve indicator<br>- Performance deviation | - Design (actuator)<br>- Quality and process control<br>- Choice of latching valve (bi-stable) |
| | Deviating performances (e.g. manoeuvring time, $\Delta p$, reduced life cycle) | - Pressure measurement<br>- Reduced mass flow rate<br>- Deviation in engine functioning | - Design analysis<br>- Quality assurance<br>- Material selection<br>- Life cycle analysis<br>- Component tests |
| Valve: housing | Crack propagation | See piping | See piping |
| | Burst | See piping | See piping |
| | Low cycle fatigue | See piping | See piping |
| Valve: obturator | Oscillations | - Pressure measurements<br>- Position measurements | - Design<br>- Dynamic analysis<br>- Flow analysis |
| | Jamming or icing | - Pressure measurements<br>- Position measurements<br>- Performance decay | - Design analysis<br>- Clearance analysis<br>- Material selection, conforming to propellant specifications<br>- Pollution control<br>- Humidity control<br>- Thermal differential analysis |

**Table 10: Liquid propulsion for launchers component failure modes**
*(continued)*

| Component type | Failure mode | Failure detection | Failure prevention |
|---|---|---|---|
| Valve: main seal and seat | Pollution | - Pressure measurement<br>- Leakage measurement | - Contamination control<br>- Conforming to propellant specifications |
| | Damage | - Pressure measurement<br>- Leakage measurement | - Contamination control<br>- Conforming to propellant specifications<br>- Assembly procedures<br>- Design<br>- Material selection |
| | Cracking | - Pressure measurement<br>- Leakage measurement | - Design analysis<br>- Thermal-mechanical analysis<br>- Material selection<br>- Assembly procedures<br>- Quality control |
| | Deformation, including creep | - Pressure measurement<br>- Leakage measurement | - Design analysis<br>- Thermal-mechanical analysis<br>- Material selection<br>- Assembly procedures<br>- Ageing analysis<br>- Creep analysis<br>- Quality control |
| Valve: obturator shaft | Jamming or icing | See Obturator | See Obturator |
| | Buckling | - Pressure measurement<br>- Loss of functionality<br>- Performance deviations | - Design analysis<br>- Mechanical analysis |
| Valve: dynamic sealing | Leakage | See Main seal and seat | See Main seal and seat |
| Pressure regulator | Deviation in functioning (e.g. wrong pressure, wrong mass flow rate) | - Pressure measurement<br>- Deviation in engine functioning | - Design analysis<br>- Quality control<br>- Component tests<br>- Cleanliness control (filters) |
| | Internal leakage | As for valves | As for valves |
| | External leakage | As for valves | As for valves |
| | Stick-slip behaviour | Pressure measurement (sudden pressure changes) | - Tribology<br>- Material selection<br>- Gap analysis<br>- Thermal differential analysis |
| Ground-board coupling devices | Unintentional decoupling | - Visual<br>- Position indicators | - Design analysis<br>- Component tests<br>- System tests |
| | No decoupling | - Visual<br>- Position indicators | - Design analysis<br>- Component tests<br>- System tests |
| | Leakage | As for valves | As for valves |

**Table 10: Liquid propulsion for launchers component failure modes**
*(continued)*

| Component type | Failure mode | Failure detection | Failure prevention |
|---|---|---|---|
| Calibrating orifice | Flow blockage | - Performance deviation<br>- Pressure measurements | - Cleanliness<br>- Filters<br>- Adherence to fluid specifications<br>- Humidity control<br>- Operational procedures (flushing) |
| | Deviation in $\Delta p$ or mass flow rate | - Performance deviation<br>- Pressure measurements | - Cleanliness<br>- Filters<br>- Flow design analysis<br>- Humidity control<br>- Operational procedures (flushing) |
| Filter | Too high $\Delta p$ | - Performance deviation<br>- Pressure measurements | - Contamination tree analysis<br>- Design analysis<br>- Cleanliness<br>- Fluid specifications<br>- Humidity control<br>- Operational procedures (flushing) |
| | Particle generation | - Contamination measurement<br>- Failure of downstream components | - Material selection and compatibility<br>- Design<br>- Quality control |
| | Buckling or rupture | - Pressure measurement<br>- Contamination<br>- Failure of downstream components<br>- Performance deviation | - Design<br>- Material selection<br>- Mounting procedures<br>- Operational procedures<br>- Quality control |
| Piping (for liquids and cold gas) | Burst | - NDI<br>- Visual inspection<br>- Loss of pressure | - Design analysis<br>- Tests<br>- Inspection of welds |
| | Crack initiation and propagation | - NDI<br>- Visual inspection<br>- Loss of pressure | - Design analysis<br>- Material selection<br>- Stress corrosion analysis<br>- Inspection of welds<br>- Implementation of a fracture control plan |
| | Vibrations | - Pressure measurement<br>- Accelerometers | - Dynamic analysis<br>- Design analysis<br>- Design of support fixtures Damping, shape of the piping<br>- Material selection |
| | Low cycle fatigue (thermal cycles) | - Loss of pressure<br>- Strain gauge measurements | - Design, within the plastic limit of the material<br>- Material selection |

**Table 10: Liquid propulsion for launchers component failure modes**
*(continued)*

| Component type | Failure mode | Failure detection | Failure prevention |
|---|---|---|---|
| Connections with bellows | Burst | - NDI<br>- Visual inspection<br>- Loss of pressure | - Dimensioning<br>- Quality control (material thickness)<br>- Quality of welds |
| | Crack propagation | - NDI<br>- Visual inspection<br>- Loss of pressure | - Quality control<br>- Stress corrosion control<br>- Material and process selection<br>- Inspection of welds |
| | Buckling | - Visual inspection<br>- NDI | - Dimensioning<br>- Quality control |
| | Vibration | - Pressure measurements<br>- Accelerometer measurements | - Dynamic analysis<br>- Design |
| | Low cycle fatigue | - Loss of pressure | - Design, within the plastic limit of the material<br>- Material selection |
| Joints and seals | Leakage | - Leak tightness control<br>- Pressure loss<br>- Thermal measurements | - Design<br>- Process and manufacturing control<br>- Mounting procedures |
| | Loss of mechanical integrity | - Visual<br>- NDI<br>- Engine failure | - Design<br>- Process and manufacturing control<br>- Mounting procedures |
| | Generation of particulate material | - $\Delta p$<br>- Failure of downstream components | - Material and process selection and control<br>- Cleanliness, mounting procedures |
| Support fixtures | Loss of integrity | - Visual<br>- NDI<br>- Functional loss of the supported component or subsystem | - Design<br>- Manufacturing and process control<br>- Special measures during storage and transport |
| | Change of rigidity | - Accelerometers<br>- Measurement of vibration levels and frequencies | - Design<br>- Tribology<br>- Material and process control |
| | Crack propagation | - Visual<br>- NDI<br>- Functional loss of the supported component or subsystem | Fracture control |
| Heat exchanger | As for piping | As for piping | As for piping |

**Table 10: Liquid propulsion for launchers component failure modes**
*(continued)*

| Component type | Failure mode | Failure detection | Failure prevention |
|---|---|---|---|
| Thermal protection | Debonding with or without ejection of parts | - Pressure anomalies<br>- Visual inspection<br>- Formation of ice | - Quality control<br>- Design<br>- Material selection<br>- Mounting procedures and processes |
| | Cracks | - Pressure anomalies<br>- Visual inspection<br>- Formation of ice | - Quality control<br>- Design<br>- Material selection<br>- Mounting procedures and processes |
| | No He purge (in the case of a gas gap or MLI) | - Cryopumping<br>- Visual inspection<br>- Pressure anomalies<br>- Formation of ice | Quality and flow control |
| | Outgassing anomalies of the insulation | - Visual (vacuum test)<br>- Pressure anomalies | - Design<br>- Quality control |
| | Handling damage | - Visual<br>- NDI<br>- Pressure anomalies | Handling and manufacturing procedures |
| POGO suppression device | Blockage of buffer entrance or gas outlet | Pressure or mass flow rate fluctuations | - Cleanliness control<br>- Quality assurance<br>- Design (pollution tolerant) |
| | Loss of feed gas pressure | Pressure or mass flow rate fluctuations | - Design e.g. redundant feed lines<br>- Quality assurance<br>- Leak testing |
| Burst disk | Not opening at design pressure | - Pressure measurement<br>- Flow rate measurement | - Design analysis<br>- Quality control |
| | Leakage | Pressure measurement | - Design analysis<br>- Quality control |
| | Excessive generation of particles (size, amount) | Failure of downstream components | - Design analysis<br>- Quality control |
| Harness | No transmission of power, information or commands | - Continuity check<br>- Resistance measurement | - Design analysis<br>- Quality control<br>- Process control<br>- Process selection |
| | Distortion of information or power | - Voltage and current measurement<br>- Output signal measurement | - EMC tests<br>- Design analysis<br>- Quality control |
| Gas generator and pre-burner | As for chamber and injectors | As for chamber and injectors | As for chamber and injectors |

**Table 10: Liquid propulsion for launchers component failure modes**
*(continued)*

| Component type | Failure mode | Failure detection | Failure prevention |
|---|---|---|---|
| Actuators | Jamming | Displacement or speed measurement | - Design analysis<br>- Material selection<br>- Quality assurance and control<br>- Tribology |
| | Goes to wrong positions | External displacement measurement | - Design and control analysis<br>- Quality assurance and control |
| | Wrong displacement speed | - External measurement of displacement versus time<br>- Pressure and flow or voltage and current measurement | - Tribology<br>- Design analysis<br>- Quality assurance and control |
| Propulsion system controller | No or erroneous control functions | Unexpected behaviour of the propulsion system | - Design analysis, including voting policy and redundancy<br>- Quality assurance and control |

## 6.6.15 Thrust vector control (TVC)

### 6.6.15.1 General

For TVC, subclause 4.3.8. applies.

NOTE The combustion chamber or engine with the gimbal joint or ball joint is deflected on command by actuators.

### 6.6.15.2 Roll control

Movable nozzles can also be part of a turbine exhaust system. Tap-off gases from the engine or from the tank can also be used for roll control.

## 6.6.16 Interfaces

### 6.6.16.1 General

a. The interface definitions and requirements should be documented in the interface control document.

NOTE See ECSS-E-10 Part 4 for details.

b. If a. is not carried out, justification shall be provided.

c. The definitions and requirements described in a. shall apply equally to the stage and the engine or engines.

### 6.6.16.2 Geometrical interface

a. The interface between all subsystems of the stage, including the engine and its components, shall conform to the geometrical requirements.

b. The definition of the geometrical interfaces shall take into account the static and dynamic behaviour of the subsystems for the extreme envelope for the whole mission.

#### 6.6.16.3 Stage subsystem and engine subsystem interfaces

##### 6.6.16.3.1 Mechanical interfaces

a. The loads on the interface (e.g. weight, thrust, side loads, ignition peaks, and vibrations) between all the stage and engine interfaces shall be derived from the extreme envelope for the whole mission.

b. Provision a. shall be performed early in the development (project Phases A and B) and verified during the qualification.

NOTE This can include a re-definition of the interface loads.

c. The actuation forces, response times and deflections for the gimbaling of the engine shall be derived from the extreme envelope for the whole mission.

d. The combination of extremes that are independent of each other and cannot occur simultaneously shall be precluded.

e. The constraints on geometry, loads, deflections, and response times shall

1. be identified, and
2. include dynamic effects, shocks and side loads.

##### 6.6.16.3.2 Fluid interfaces: overview

Interfaces for fluids that flow between stage subsystems include

- propellants,
- pressurant gases,
- RCS fluids,
- fluids to actuate systems, subsystems or components,
- fluids to energize the TVC system,
- fluids to purge the engine or engine components,
- fluids to chill-down the engine or engine components, and
- venting or draining of fluids.

##### 6.6.16.3.3 Fluid interfaces: specification

For all the fluids identified in 6.6.16.3.2, the following shall be specified for the whole mission:

a. the range of mass flow rates;

b. the range of pressures;

c. the range of temperatures;

d. the range of pressure and temperature amplitudes during oscillations;

e. the range of frequencies during oscillations;

f. cleanliness;

g. the type of dissolved gas;

h. the range of the amount of dissolved gas.

##### 6.6.16.3.4 Electrical interfaces: overview

The electrical interfaces between the stage and subsystems are:

- command lines, e.g. to activate valves, to ignite the detonator on a pyrotechnic igniter, to activate a spark plug;
- monitoring lines to measure e.g. temperatures, pressures, accelerations, deformations and deflections;
- the numerical bus for computer controlled activities;
- power, e.g. to deliver power to the stage or to deliver power to the engine;

- the geometry (e.g. pin configuration) of the various plugs.

6.6.16.3.5 Electrical interfaces: specification

a. For the command lines (see 6.6.16.3.4), the following shall be specified:
   1. the range of the current;
   2. the range of the voltage;
   3. the range of the resistance;
   4. the range of the rate of change of the current;
   5. the range of the impedance;
   6. the duration.

b. For the monitoring lines (see 6.6.16.3.4) the following shall be specified:
   1. the sampling rate;
   2. the measurement range;
   3. the type of measurement (e.g. effect on cables, plugs).

c. For the electrical power (see 6.6.16.3.4) the following shall be specified:
   1. power;
   2. voltage;
   3. duration.

6.6.16.3.6 Thermal interfaces

The thermal interfaces shall conform to the subsystem and system requirements.

### 6.6.16.4 Interface between the propulsion system and the GSE

6.6.16.4.1 General

The interface between the propulsion system and the GSE shall conform to the geometrical requirements for the propulsion system and the GSE.

6.6.16.4.2 Mechanical interface

The loads on the interface between the propulsion system and the GSE shall be defined by an analysis that takes into account

a. ambient conditions (e.g. wind),
b. the weight of connecting lines,
c. the pressures,
d. the temperatures,
e. the mass flow rates,
f. the loading procedures, and
g. the disconnection procedures.

6.6.16.4.3 Fluid interfaces: overview

Interfaces between the propulsion system and the GSE for fluids that flow from the GSE into the propulsion system or vice versa include

- propellants,
- pressurant gas,
- conditioning fluids, and
- fluids to actuate systems, subsystems or components.

6.6.16.4.4 Fluid interfaces: specification

a. For the fluids listed in 6.6.16.4.3, the following shall be specified:
   1. chemical composition;
   2. range of mass flow rates;
   3. range of pressures;
   4. range of temperatures;
   5. cleanliness;
   6. the type of dissolved gas;
   7. the range of the amount of dissolved gas

b. As in case of launch-abort, the launcher is reset to a safe condition, umbilical connections that are disconnected by the lift-off itself (e.g. "snap-off" connections) should be used.

6.6.16.4.5 Electrical interfaces: overview

The electrical interfaces between the propulsion system and the GSE are:

- monitoring lines (e.g. temperatures, pressures, fill level);
- power (e.g. heating, loading batteries);
- geometry (pin configuration for plugs).

6.6.16.4.6 Electrical interfaces: specification

a. For the monitoring lines (see 6.6.16.4.5) the following shall be specified:
   1. the sampling rate;
   2. the measurement range;
   3. the type of measurement (e.g. effect on cables and plugs).

b. For the electrical power (see 6.6.16.4.5) the following shall be specified:
   1. power;
   2. voltage;
   3. duration.

## 6.6.17 Monitoring and control system

### 6.6.17.1 Overview

The functions of the monitoring and control system can include:

- monitoring the state of a subsystem or system;
- collecting information for further processing, e.g. transmission to ground;
- comparing the state of the subsystem or system with the intended one;
- activating equipment to suppress deviations from the intended state of the subsystem or system.

These functions are executed by the on-board computers (OBCs). The OBCs receive the information about the system or subsystem from the monitoring system.

The comparison within the OBC is performed using dedicated software.

### 6.6.17.2 General

a. The software used to perform the comparison within the OBC shall conform to the system and propulsion system requirements.

b. As a result of the comparison process, the software shall generate, and send to the equipment (e.g. valves, actuators, igniters), the commands to set the propulsion system into the intended state.

c. In selecting the monitoring and control system the following parameters shall be taken into account:

1. power to perform the functions;
2. response time;
3. dynamic coupling between physical parameters, command and resulting action.

d. For the monitoring and control system a FMECA shall be made and catastrophic failures shall be avoided.

NOTE For FMECA, see ECSS-Q-30-02.

#### 6.6.17.3 Monitoring system

a. An analysis shall be made to establish:

1. the type of monitoring devices to use,
2. the locations for installing the monitoring devices.

b. The analysis specified in a. shall conform to the system and propulsion system requirements.

c. It should be ensured that the environment in which the monitoring equipment functions conforms the requirements for the monitoring equipment or vice versa.

d. If c. is not met, measures shall be taken to adjust the environment of the monitoring equipment (e.g. heating, cooling and venting).

e. The reliability of the monitoring system shall conform to the propulsion subsystem and system requirements.

#### 6.6.17.4 Control system

##### 6.6.17.4.1 Overview

Control systems for launcher propulsion are:

- pneumatic;
- electric;
- hydraulic.

##### 6.6.17.4.2 Pneumatic control systems

a. General

1. The selection of the fluid shall take into account the following:
   (a) compatibility of the fluid with the propellants;
   (b) thermodynamic behaviour (cooling during expansion);
   (c) total mass of the fluid.
2. It shall be ensured that he fluid does not contain condensable gases (e.g. $H_2O$, $CO_2$).

   NOTE These gases can condense, freeze and hamper proper operation.

b. Selection of storage pressure

The storage pressure shall be selected, based on the following parameters:

1. availability of high pressure gas tanks;
2. the thermodynamic characteristics of the fluid (cooling during expansion);
3. the availability of pressure regulators (pressure drop and mass flow rate).

c. Selection of command pressure

The command pressure shall be selected, based on the following parameters:

1. the power to perform the functions and actuator size;
2. thermodynamic behaviour (cooling during expansion);
3. the amount of residual gas.

d. Fluid mass

1. For determining the amount of pneumatic control fluid, the following parameters shall be taken into account:
   (a) the mission requirements specify the frequency of operation of the control system, and from this the maximum amount of gas for the most commanding mission is determined;
   (b) leak losses;
   (c) residual fluid at EOL.
2. A margin for uncertainty shall be established and taken into account in the initial design stage (project Phases A and B).

e. Dynamic aspects

1. As for during the operation of the control system when pressure fluctuations are created in the system, it shall be ensured that all components in the pneumatic control system are compatible with these pressure fluctuations and do not malfunction (e.g. inadvertent opening of relief valves, malfunctioning of components and closing of pressure regulator).
2. The design shall ensure that when the control system is operated, inadvertent couplings are not introduced:
   (a) internally (pressure regulator and check valves);
   (b) externally (e.g. tank pressurization system).

f. Ground operations

To ensure proper decoupling and closing of the non-return valve that connects the low pressure part of the pneumatic system to the GSE, the system shall function as specified on the low GSE pressure.

NOTE During ground operations, the pneumatic system is operated through a low pressure fluid supply system.

#### 6.6.17.4.3 Electric control systems

It shall be ensured that all electrical components function as specified in the specified environment (e.g. electric cryogenic valve or components exposed to propellant vapours).

NOTE For requirements on electric control systems, see ECSS-E-20.

#### 6.6.17.4.4 Hydraulic control system

a. General

1. The selection of the fluid shall take into account the following parameters:
   (a) the operating temperature range;
   (b) the compatibility of the fluid with the propellants and materials;
   (c) the total mass of the fluid.
2. The fluid shall not contain contaminants that prevent the system from functioning as specified,
3. The fluid shall not contain contaminants that cause failures of the system.

b. Selection of operating pressure

The selection of the operating pressure shall be based on:

1. the availability of high pressure tanks and accumulators;
2. the power to be used and size of the actuators;
3. the amount of residuals (open cycles).

c. Fluid mass (open cycle)

1. To determine the amount of hydraulic control fluid the following parameters shall be taken into account:
   (a) the mission requirements specify the frequency of operation of the control system, and from this the maximum amount of fluid for the most demanding mission is determined;
   (b) leak losses;
   (c) residual fluid at EOL.
2. A margin shall be established and taken into account.

   NOTE This margin is especially important at the initial design stage (project Phases A and B).

d. Dynamic aspects

1. As for pressurised systems, pressure fluctuations can be severe (water-hammer effect), therefore the limit for the pressure fluctuations shall be established.
2. The design of the control system shall ensure that the pressure fluctuations are below the limit specified in 1.
3. It shall be ensured that all components in the hydraulic control system are compatible with the pressure fluctuations.

## 6.7 Ground support equipment

### 6.7.1 General

a. The design of the propulsion ground support equipment (GSE) shall conform to the safety requirements of the facility where it is operated.

b. The GSE shall conform to ISO 14625 and ISO 1539.

### 6.7.2 Fluid

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

b. The GSE design shall provide dedicated evacuation lines to the facility in case of operation of any relief valve (see ECSS-E-70).

c. Any contact between materials which, when coming into contact with each other, can cause a hazard, shall be avoided by design.

d. The connecting lines shall avoid catastrophic failures by design and shall conform to the system requirements and launch safety requirements.

e. The procedures and the design of the equipment shall be such that inadvertent operation and pressurization of the subsystems is avoided.

   NOTE This is intended to avoid all risks.

f. The GSE design, functioning and procedures shall ensure that fluids are delivered to the launcher or spacecraft according to their specifications (contamination level, pressure and temperature).

   NOTE Annex A lists specification for fluids.

g. The GSE shall be designed such that disconnection of lines
   1. does not pose risks, and
   2. does not cause pollution.

### 6.7.3 Electrical

a. The system shall enable access to verify electrical continuity and functionality of all electrically operated equipment.

b. The procedures to operate, and the design of the equipment shall be such that inadvertent activation of the systems and subsystems is prevented.

   NOTE This prevents additional risks.

c. If the GSE is intended to be used in the vicinity of inflammable or explosive materials, it shall be explosion proof.

## 6.8 Verification

### 6.8.1 General

For general requirements on the verification of liquid propulsion systems for launchers, see subclause 4.6.1.

### 6.8.2 Verification by analysis

For requirements on verification by analysis of liquid propulsion systems for launchers, see subclause 4.6.2.

### 6.8.3 Verification by test

#### 6.8.3.1 Overview

In addition to 4.6.3, the following applies to liquid propulsion systems for launchers.

#### 6.8.3.2 Test objectives

The tests shall provide the data for obtaining, as a minimum, the following parameters for liquid propulsion systems during ground tests:

a. thrust versus time;

b. mass flow rate versus time for each propellant;

c. chamber pressure versus time;

d. pump inlet and outlet pressures for each propellant;

e. tank pressures and temperatures versus time (the pressurant tank included);

f. inlet and outlet pressures for the gas generators or pre-burners;

g. valve manoeuvring times;

h. turbo-pump spool rotational speed and axial position;

i. coolant system outlet temperatures;

j. moments and side forces generated by the engine;

k. the thermal, acoustic and vibration environment generated by the engine, during steady state and transient operations;

l. propellant and pressurant gas leakage rates.

#### 6.8.3.3 Test steps

The verification by test, of whether a system, subsystem or component conforms to the requirements, according to the compliance matrix, comprises the following three steps (see 4.6.3) of which the development tests are specific for liquid propulsion systems:

- Development tests.

  During development tests, the system, subsystem, or component is tested within the qualification envelope with the following objectives:

  - to verify the functioning of the system, subsystem, or component under the transient and steady state conditions of the extreme envelope;
  - to gain confidence in the design and selected materials to undergo qualification testing;
  - to optimize the design with respect to dimensioning, performance and cost;
  - to verify the suitability of the manufacturing processes and procedures;
  - To verify that the product conforms to the storage and shelf life requirements;
  - to verify that the product is compatible with the reliability target;
  - to ensure that the motor conforms to the safety requirements of subclause 4.9 and the safety tests.

- Ground qualification tests

  The objectives of the ground qualification tests is described in 4.6.3.1.h.2.

- Qualification during flight

  The objective of the flight qualification tests is described in 4.6.3.1.h.3.

#### 6.8.3.4 Tests on systems, subsystems and components

Table 11 identifies the type of verification by test that should be performed for components, subsystems and systems of liquid propulsion systems.

NOTE Details on the verification of qualification envelope requirements and acceptance tests are given in subclause 4.6.3.2.

**Table 11: Test on liquid propulsion for launchers systems, subsystems and components**

| | **Item** | **Verification of requirements for qualification envelope** | **Acceptance** |
|---|---|---|---|
| 1.1 Materials | Metals | Only characterization in case of special requirements, e.g. cryogenic conditions, new processes | |
| | Fibres | - | |
| | Chemicals | - | |
| | Pyrotechnic mixtures | Characterization according to approved standards | |
| | (Pre-impregnated) fiber material (e.g. felt, cloth) | Characterization only in special cases | |

**Table 11: Test on liquid propulsion for launchers systems, subsystems and components** *(continued)*

| | Item | Verification of requirements for qualification envelope | Acceptance |
|---|---|---|---|
| 1.2 Components | Of the shelf items (standard, non-critical, e.g. bolts, simple instruments, relief valve, O-rings) | Characterization if the standard component is used outside the suppliers' specification | Lot acceptance test or quality assurance by the supplier |
| | Of the shelf items (critical, e.g. pyrotechnic devices, items on the FMECA critical path) | Characterization | Lot acceptance test or quality assurance by the supplier |
| | Specially manufactured components | | |
| | Valve | Characterization | - Pressure proof test<br>- Leak test<br>- Response time |
| | Pressure regulator | Characterization | - Pressure proof test<br>- Leak test<br>- Standard performance test |
| | Gimbal joint | Characterization | - Dimensional control<br>- NDI |
| | Burst disk | | Lot acceptance test |
| | Piping | | - Verification at engine level<br>- Tuning and acceptance test |
| | Heat exchangers | Characterization | - Verification at engine level<br>- Tuning and acceptance test |
| | Instrumentation | | - Acceptance test<br>- Calibration |
| | Harness | | Continuity measurement |
| | High pressure tank | Characterization under extreme pressure | - Proof pressure test<br>- NDI |
| | Specially manufactured components: | | |
| | Bearings | Endurance test, extreme speed test under combinations of maximum axial and radial loads | NDI |
| | Seals | Characterization under extreme conditions, including margin tests and failure tests | NDI |
| | Turbine disks | Over speed until burst or unbalance | Proof spinning test |
| | Impellers | Over speed until burst or unbalance | Proof spinning test |
| | Inducers | Over speed until burst or unbalance | Proof spinning test |
| | Pump housing | Characterization under extreme pressure (Maximum design pressure) | Proof test |

**Table 11: Test on liquid propulsion for launchers systems, subsystems and components** *(continued)*

| | Item | Verification of requirements for qualification envelope | Acceptance |
|---|---|---|---|
| 2. Subsystems | Subsystems with welded, brazed or screwed connections | | Leak test, NDI |
| | Thrust chamber assembly | - Complete qualification within the system testing<br>- Hot firing test | - Pressure test<br>- Leak test<br>- Weld inspection<br>- Flow characterization of individual injector elements<br>- Firing tests |
| | Thermal protection and barrier coating (internal) | - Post-flight or post-firing-evaluation<br>- At engine level: post-firing inspection | - Dimensional control<br>- Tests of representative bonds (samples) |
| | Thermal protection (external) | - Post-flight evaluation<br>- At motor level: firing test | Verification of bonds (samples) |
| | Turbo pump | - Full-scale turbo pump test with gas generator (pre-burner)<br>- Hydraulic tests on pumps<br>- Turbine fluid dynamic tests<br>- Rotor dynamic tests<br>- Chill-down tests (only for cryogenic equipment) | - Leak test<br>- NDI |
| | Gimbal joint and actuation system | - Characterization of mass, dimensions, stiffness, friction moment under operational conditions, thermo-mechanical behaviour connected to the engine<br>- Firing test | |
| | Igniter (pyrotechnic) | - Qualification according to ECSS-E-30 Part 6A subclause 4.11.7<br>- Igniter firing tests shall demonstrate its proper functioning, e.g. response times<br>- Safety tests, cold tests<br>- In the case of redundant ignition chains, demonstration of proper functioning with both chains and a single chain<br>- Motor firing test | - NDI<br>- Lot acceptance tests for series produced igniters |

**Table 11: Test on liquid propulsion for launchers systems, subsystems and components** *(continued)*

| | **Item** | **Verification of requirements for qualification envelope** | **Acceptance** |
|---|---|---|---|
| | Igniter (electric) | - Characterization<br>- Igniter firing tests shall demonstrate its proper functioning, e.g. response time<br>- Electromagnetic tests<br>- In the case of redundant ignition chains, demonstration of proper functioning with both chains and a single chain<br>- Motor firing tests | - NDI<br>- Leak tightness test |
| | Gas generator and pre-burner | - Characterization under extreme pressure (structural part)<br>- Verification of the interface with the engine<br>- Verification of leak tightness<br>- Firing of the gas generator or pre-burner<br>- Motor firing test | - Proof pressure test<br>- Leak test<br>- NDI |
| | Propellant tanks | - Proof pressure test<br>- Fill and drain test<br>- Reverse pressure tests for common bulkhead tanks | - NDI<br>- Dimensional control<br>- Mass determination<br>- Leak test |
| | Propellant feed system | - Proof pressure test<br>- Pressure drop test<br>- water-hammer test<br>- Start-up and shutdown test<br>- Chill-down test for cryogenic engines | - NDI<br>- Dimensional control<br>- Mass determination<br>- Leak test |
| | Pressurization system | - Functional test in the qualification envelope<br>- Dynamic test to verify the stability of the pressurization loop | - Leak test<br>- NDI |
| | Measurement and control system | Functional test | - Electrical continuity<br>- Leak tests for hydraulic and pneumatic parts<br>- Verification of response times<br>- NDI |

**Table 11: Test on liquid propulsion for launchers systems, subsystems and components** *(continued)*

| | Item | Verification of requirements for qualification envelope | Acceptance |
|---|---|---|---|
| 3. Systems | Engine | Ambient tests<br>Mechanical mock-up test<br>Firing tests (with TVC, ground and flight) | - Dimensions<br>- Mass<br>- Electrical continuity Leak-tightness<br>- Individual firing tests |
| | Propulsion system | - Ambient test<br>- Functional test of the stage with engine firing<br>- Thermal budget test for cryogenic systems | - Dimensional check<br>- Leak test<br>- Electrical continuity<br>- Dry mass |

### 6.8.4 Verification by inspection

For requirements on verification by inspection of liquid propulsion systems for launchers, see subclause 4.6.4.

## 6.9 Production and manufacturing

### 6.9.1 Overview

For production and manufacturing of liquid propulsion systems for launchers, this subclause applies. In addition to 4.7, subclauses 6.9.2 to 6.9.6 apply.

For the quality of the production and manufacturing methods, see ECSS-Q-20A subclause 4.7, and Clauses 5 and 6.

For the pressurized structural components of a liquid propulsion system or subsystem, see subclause 4.8 of ECSS-E-30 Part 2A.

### 6.9.2 General

a. The loads during manufacturing, handling, test and transport on structural elements, components, subsystems and systems shall be analysed.

b. It shall be ensured that the manufacturing process, handling and transport do not contaminate or damage the product.

### 6.9.3 Cleanliness

a. The components and elements of the propulsion system that are sensitive to pollution and contamination shall be identified.

b. The upstream components and elements of the propulsion system that can cause pollution or contamination of sensitive downstream components and elements shall be identified.

c. 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.

d. It shall be ensured that the components and elements that come into contact with reactive chemicals, for example, oxygen, are cleaned.

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

### 6.9.4 Temperature controlled manufacturing and assembly

a. Elements to be manufactured under temperature controlled conditions:

1. shall be identified; and
2. should be manufactured under such temperature controlled conditions.

b. Elements to be assembled with other elements under temperature controlled conditions:

1. shall be identified; and
2. should be assembled under such temperature controlled conditions.

NOTE For elements with very strict dimensional tolerances or for large elements, thermal expansion or contraction can cause problems when assembling the elements with other parts.

c. If a.2. or b.2. are not carried out, justification shall be provided.

### 6.9.5 Assembly under cleanroom conditions

a. The minimum cleanroom conditions for the assembly of the elements and components that have undergone cleansean with regard to contamination and pollution control (see 6.9.3) shall be

1. established, and
2. applied.

NOTE For cleanroom conditions, see ISO 14644-1.

b. It shall be assured that the assembly room shall conform to the conditions specified in a.

c. After assembly the assembled components and elements shall be sealed or packaged before leaving the cleanroom.

### 6.9.6 Sealing

a. For sealing elements, components or parts, special sealing devices (e.g. caps and plugs) shall be designed and used to ensure proper sealing and prevent pollution or contamination.

b. It shall be ensured that the sealing devices themselves do not introduce pollution or contamination.

c. The sealing element shall be easily identified as such (e.g. special colour, fitted with a coloured flag).

## 6.10 In-service

### 6.10.1 Overview

In addition to subclause 4.8, this subclause applies to liquid propulsion system for launchers.

### 6.10.2 Operations

#### 6.10.2.1 Flight preparation

##### 6.10.2.1.1 Check-out of interfaces with the GSE

a. The integrated propulsion system shall be connected to the GSE.

b. The functioning of all interfaces shall be verified according to approved procedures (e.g. launch facility operator).

c. Any anomaly shall be recorded, investigated and corrected.

##### 6.10.2.1.2 Pre-launch operation

a. The launcher and the platform may be moved to the launch site after the following have been established:

1. The propulsion system is integrated into the stage as specified.

2. All interfaces with the GSE conform to the system and propulsion subsystem requirements.
3. The stage is connected to the GSE as specified.
4. The status of the propulsion system conforms to the requirements for its initial status.
5. The tanks are filled with storable propellants.

b. The maximum time and the environmental conditions (e.g. temperature, wind, humidity) under which the launcher can stay on the launch pad shall be specified.

c. If cryogenic propellants are used, the GSE shall be chilled down according to approved procedures.

d. The cryogenic tanks shall be filled according to approved procedures.

e. For the first stage, the propulsion system shall be chilled down according to approved procedures.

NOTE Usually, cryogenic upper stages are chilled down in flight, before ignition. In some cases a pre-chill-down of upper stages is performed on ground.

f. The tanks shall be pressurized (ground pressurization).

g. The pyrotechnic devices (if present) shall be armed.

h. Cryogenic top-up shall be performed to ensure that the tanks are filled to the correct level before lift-off.

i. For the first stage, the engine or engines may be started, the start-up and proper functioning may be verified.

j. Depending on the operating status of the first stage engine or engines, a decision to proceed with the launch shall be made.

k. In case it is decided not to launch, abort procedures shall be initiated.

NOTE 1 During the pre-launch operation, certain functions that are initially provided by ground systems are taken over by on-board systems (e.g. power supply or the command system).

NOTE 2 Depending on the launch procedures, the propulsion system can be disconnected from the GSE on command before lift-of or automatically by the lift-of of the launcher.

l. Back-up procedures that enable the flight preparation to be continued, in case of minor anomalies during the pre-launch operation should be defined and qualified.

#### 6.10.2.1.3 Launch abort

a. In case of launch abort,

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

b. 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 and taken into account in the propulsion system requirements.

#### 6.10.2.2 In-flight operation

##### 6.10.2.2.1 Control of an upper stage propulsion system during the operation of a lower stage propulsion system

During the operation of a lower stage propulsion system, the propulsion system of the next stage to be activated shall be maintained in or set to the specified condition for ignition, including:

a. pressurization of the propellant tanks;

b. chill-down of the propulsion system in the case of cryogenic propellants;

c. venting of propellant gases to maintain the specified propellant conditions (pressure and temperature) in the case of cryogenic propellants;

d. arming of a pyrotechnic igniter (if present and in case arming has not been performed before launch);

e. filling the engine feed lines with liquid propellant.

##### 6.10.2.2.2 Ballistic phase overview

In addition to 4.8.4.2.2, subclauses 6.10.2.2.3 and 6.10.2.2.4 apply to in-flight operations of liquid propulsion systems for launchers.

The ballistic phase concerns the period in which no main propulsion system operates. During the ballistic phase, small thrusts can be generated by small thrusters or venting or purging of gas.

##### 6.10.2.2.3 Ballistic phase: propulsion system activation

a. If the propulsion system is activated at the end of a ballistic phase, it shall be assured that before such an activation, the propellants are positioned at the outlets of the propellant tanks.

b. For a non-spinning stage where no PMD is present in the tanks, a small thrust shall be applied to the stage in order to position the propellant at the outlets of the tanks before starting to activate the propulsion system.

NOTE For a spinning stage, the position of the propellant is known, and the tank outlets may be positioned at the appropriate locations in the tanks.

For a non-spinning stage that does not undergo any thrust, the position of the propellants in the tanks is only known when the tanks have been provided with a PMD.

For a non-spinning stage where there is no PMD in the tanks, it is not known where in the tanks the propellants are located. For such stages, a small thrust is applied to the stage to position the propellants at the outlets of the tanks before starting to activate the propulsion system.

c. The ignition sequence shall not be started until it is ensured that:

1. the propellant feed lines are completely filled with liquid propellant;
2. the propellant conditions at the engine valves conform to the engine requirements.

NOTE 1 For cryogenic systems this can imply flushing the propellant lines (and engine) for some time with dump-propellant or re-circulated propellant.

NOTE 2 Depending on the propellants (hypergolic or not) and the engine cycle (e.g. gas generator, staged combustion, expander) the ignition sequence is different.

6.10.2.2.4 Ballistic phase: engine re-ignition

If an engine is intended to be re-ignited after a ballistic phase, it shall be verified before re-ignition that the engine does not contain frozen or condensed combustion products, remainders of propellants or other fluids that may freeze, condense or detonate (e.g. $H_2O$, $CO_2$, and nitrates).

NOTE This can be accomplished by e.g. flushing the engine directly after shutdown with He or by heating the engine.

6.10.2.2.5 In-flight measurements: overview

The objectives of in-flight measurements are:

- to provide information in case of anomalies,
- to provide health monitoring,
- to provide information at system level,
- to evaluate the propulsion system performance, and
- to provide information for databases.

6.10.2.2.6 In-flight measurements: parameters

The following parameters should be measured during flight:

a. Engines:
   1. chamber pressure;
   2. coolant inlet and outlet jacket pressure and temperature;
   3. pump inlet and pump outlet pressures and temperatures;
   4. turbo pump rotational speed;
   5. turbine inlet and turbine outlet pressures and temperatures;
   6. bearing temperatures (turbo pump);
   7. propellants mass flow rates;
   8. deflection angle for TVC.

b. Propellant tanks:
   1. propellant levels (high and low);
   2. propellant temperatures;
   3. propellant pressures;
   4. mass flow rates;
   5. tank pressure.

c. Pressurant tanks:
   1. pressures;
   2. temperatures.

d. Miscellaneous:
   1. acceleration at critical locations;
   2. strain gauges at critical locations;
   3. proximity measurements at critical locations.

e. Pressurization system: pressure at critical locations.

f. Valves: position of valves.

NOTE The measurement of the position of valves is very important.

6.10.2.2.7 End of mission phase: overview

In addition to 4.8.4.2.3, subclause 6.10.2.2.8 applies to the end of mission phase of liquid propulsion systems for launchers.

6.10.2.2.8 End of mission phase: passivation

a. After shut-down of the lower stages, the propulsion system shall be drained of the remaining propellants (passivation) in such a way that this does not lead to explosions or other hazardous situations.

b. After having performed the de-orbit burn, the propulsion system shall be drained (passivation) in such a way that this does not lead to explosions or other hazardous situations.

c. Liquid stages shall be passivated in their graveyard orbits.

# 7

# Liquid propulsion systems for spacecraft

## 7.1 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.

## 7.2 Functional

### 7.2.1 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.

### 7.2.2 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.

## 7.3 Constraints

### 7.3.1 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.

### 7.3.2 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.

### 7.3.3 Induced and environmental temperatures

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

### 7.3.4 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.

### 7.3.5 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.

## 7.4 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.

## 7.5 Configurational

### 7.5.1 General

#### 7.5.1.1 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.

#### 7.5.1.2 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.

#### 7.5.1.3 Replacement of parts

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

#### 7.5.1.4 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 4.3.5.

b. take into account the environmental aspects, including

1. Temperature;
2. Vibration level;
3. Humidity;
4. Corrosive environment;
5. Vacuum;
6. Outgassing;
7. Radiation.

#### 7.5.1.5 water-hammer effect

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

b. The analysis specified in a. shall be reported in accordance with Annex I.

#### 7.5.1.6 Piping

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

NOTE See subclause 7.5.1.5 above for water-hammer effect.

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

#### 7.5.1.7 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.

#### 7.5.1.8 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.

## 7.5.2 Selection

### 7.5.2.1 Reporting

The reporting shall be in accordance with Annex C.

### 7.5.2.2 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.

### 7.5.2.3 Propellant

#### 7.5.2.3.1 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.

#### 7.5.2.3.2 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.

## 7.5.3 Sizing

### 7.5.3.1 General

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

### 7.5.3.2 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 plume analysis specified in b.5. shall be reported in accordance with Annex F.

d. 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.

## 7.5.4 Development

### 7.5.4.1 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.

### 7.5.4.2 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.

## 7.5.5 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,
   2. should be verified, and

c. the plume analysis specified in b.1. shall be reported in accordance with Annex F.

d. The character and sensitivity of spacecraft sensitive elements shall be verified.

## 7.5.6 Internal contaminants

### 7.5.6.1 General

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

### 7.5.6.2 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.

## 7.5.7 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.

## 7.5.8 Components guidelines

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

NOTE Table 12 covers the component failure modes, apart from external leakage and failure to operate, generally encountered in the use of standard components.

## Table 12: 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<br>- Internal leakage | - Pressure test<br>- Position indication<br>- Internal leak test | - Electrical inhibits<br>- Cleanliness | (c) |
| Pneumatically actuated valves | - Undesired operation<br>- Internal leakage | - Pressure test<br>- Position indication<br>- Internal leak test | Cleanliness | (d) |
| Propellant fill-and-drain valves | Undesired operation | Leakage | Cleanliness | (e) |
| | Propellant mixing | Chemical reaction | Use of:<br>- different colours for components<br>- different connectors (size and thread) | (f) |
| Manually actuated valves | Internal leakage | - Pressure test<br>- Internal leak test | - Cleanliness | (g) |
| Non-return valves | Internal leakage | - Pressure test<br>- Internal leak test | - Cleanliness<br>- Design assessment | (h) |
| Pyro-valves | Undesired operation | Pressure test | - Electrical inhibits<br>- 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.<br>- Preheating of catalyst bed | (m) |
| | Catalyst poisoning | Performance loss | - Use of purified anhydrous hydrazine;<br>- 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) |

### 7.5.9 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.

### 7.5.10 Ground support equipment (GSE)

#### 7.5.10.1 General

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

#### 7.5.10.2 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.

#### 7.5.10.3 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.

### 7.5.11 Filters

#### 7.5.11.1 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)

#### 7.5.11.2 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).

### 7.5.12 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.

### 7.5.13 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).

### 7.5.14 Pyrotechnic devices

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

### 7.5.15 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).

### 7.5.16 Propellant tanks

#### 7.5.16.1 Reporting

The reporting shall be in accordance with Annex D.

#### 7.5.16.2 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.

#### 7.5.16.3 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.

#### 7.5.16.4 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.

#### 7.5.16.5 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.

### 7.5.17 Thrusters

#### 7.5.17.1 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).

#### 7.5.17.2 Thruster alignment

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

#### 7.5.17.3 Thrust mismatch

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

#### 7.5.17.4 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

#### 7.5.17.5 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.

#### 7.5.17.6 Catalyst bed heating

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

#### 7.5.17.7 Thermal environment

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

b. Reporting of the analysis specified in a. shall be in accordance with Annex E.

### 7.5.18 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.

### 7.5.19 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.

## 7.6 Verification

### 7.6.1 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 7.6, 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.

### 7.6.2 Verification by analysis

#### 7.6.2.1 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.

#### 7.6.2.2 Steady state

##### 7.6.2.2.1 General

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

a. Steady-state characteristics

The establishement of 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 analysis of the aspects specified in 1., reported in accordance with Annex K.
3. 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
   1. 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.)
   2. The analysis specified in 1. shall be reported in accordance with Annex E.

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. The nozzle and discharge flow analysis report specified in 1. shall be reported in accordance with Annex G.
   3. It shall be established whether protection devices are required.
   4. 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.
   5. The plume analysis, as specified in 4. shall be reported in accordance with Annex F.

f. Gauging analysis

1. Analysis shall demonstrate that the required accuracy is obtained with the on-board measurement equipment and its related data handling.
2. The thermal analysis, as specified in 1. shall be reported in accordance with Annex D.

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.

#### 7.6.2.3 Transients

7.6.2.3.1 Reporting

a. The transient analyses specified in 7.6.2.3 shall be reported in accordance with Annex I.

b. The mathematical modelling specified in 7.6.2.3 shall be reported in accordance with Annex K.

7.6.2.3.2 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.

7.6.2.3.3 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.

c. Sloshing analysis shall be reported in accordance with Annex H.

7.6.2.3.4 Spin load

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

7.6.2.3.5 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.

7.6.2.3.6 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.

### 7.6.3 Verification by test

#### 7.6.3.1 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.

#### 7.6.3.2 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.

#### 7.6.3.3 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).

#### 7.6.3.4 Cleanliness

##### 7.6.3.4.1 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).

##### 7.6.3.4.2 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.

#### 7.6.3.5 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.

#### 7.6.3.6 Contamination control

a. In case the parameters for total contamination defined 7.6.2.2 a.3.(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.

#### 7.6.3.7 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.

#### 7.6.3.8 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.

#### 7.6.3.9 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.

#### 7.6.3.10 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.

#### 7.6.3.11 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.

#### 7.6.3.12 Thruster alignment

Thruster alignment shall be tested for conformity to the requirements.

#### 7.6.3.13 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.

#### 7.6.3.14 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.

#### 7.6.3.15 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.

### 7.6.4 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.

## 7.7 Quality factors

### 7.7.1 Reliability

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

a. the probability of success of the mission;

b. design life.

### 7.7.2 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.

## 7.8 Operation and disposal

### 7.8.1 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).

### 7.8.2 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).

### 7.8.3 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 $\Delta p$ for diaphragm tanks shall not be exceeded.

### 7.8.4 Disposal

#### 7.8.4.1 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.

#### 7.8.4.2 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.

#### 7.8.4.3 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.

## 7.9 Support

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

a. Performance analysis (in accordance with Annex C);

b. Transient analysis (in accordance with Annex I);

c. Sloshing analysis (in accordance with Annex H);

d. Thermal analysis (in accordance with Annex E);

e. Plume analysis (in accordance with Annex F);

f. Gauging analysis (in accordance with Annex D);

g. Mechanical analysis;

h. User manual (in accordance with Annex J).

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.

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# 8

# Electric propulsion systems for spacecraft

## 8.1 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 AOCS.

Three operational subsystems can be distinguished:

- a propellant storage and supply subsystem, where spacecraft liquid propulsion rules are applicable (see clause 7 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 8.

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.

## 8.2 Functional

### 8.2.1 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.

### 8.2.2 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.

### 8.2.3 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. Reporting of beam divergence, as specified in a.7. shall be in accordance with Annex F.

c. 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.

d. 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.

e. Response time shall be defined with respect to:
   1. on-off operations;
   2. in thrust level.

## 8.3 Constraints

### 8.3.1 General

a. For use of electric propulsion on a spacecraft, special care shall be paid with regard to:
   1. Thruster priming, start up and restart sequences of:
      (a) thrust level;
      (b) $I_{sp}$;
      (c) power consumption;
      (d) throttleability.
   2. 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;
   3. plume effect on the spacecraft;
   4. maximum values of thermal fluxes for the power supply and thruster subsystems;
   5. electromagnetic compatibility with the spacecraft electrical subsystem and the payload.

b. the plume analysis (plume and beam), as specified in a.3. shall be reported in accordance with Annex F.

### 8.3.2 High frequency current loops

#### 8.3.2.1 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.

#### 8.3.2.2 Impact on sensitive electronics

The spacecraft electrical architecture shall consider the high frequency current loops referred in 8.3.2.1 to minimize their impact on sensitive electronics.

### 8.3.3 Thermal fluxes

a. Since the heat dissipated by the power supply subsystem can be significant even with a good efficiency, if overheating of the system is shown by the

thermal analysis, a specific layout of the spacecraft or specific devices for the cooling of the subsystem shall be provided.

NOTE Another heat source is the thruster.

b. Reporting shall be in accordance with Annex E.

### 8.3.4 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.

### 8.3.5 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.

## 8.4 Interfaces

### 8.4.1 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.

### 8.4.2 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.

## 8.5 Configurational

### 8.5.1 General

#### 8.5.1.1 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.

#### 8.5.1.2 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).

#### 8.5.1.3 Replacement of parts

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

#### 8.5.1.4 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.

#### 8.5.1.5 Water-hammer effect

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

b. The water-hammer effect analysis specified in a. shall be in accordance with Annex I.

#### 8.5.1.6 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.

#### 8.5.1.7 Multi-tanks

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

#### 8.5.1.8 Electromagnetic compatibility

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

#### 8.5.1.9 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.

### 8.5.2 Selection

#### 8.5.2.1 Reporting

The reporting shall be in accordance with Annex C.

#### 8.5.2.2 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.

#### 8.5.2.3 Propellant

##### 8.5.2.3.1 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.

8.5.2.3.2 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.

## 8.5.3 Sizing

### 8.5.3.1 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.

### 8.5.3.2 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.

c. The plume analysis, as specified in b.5. shall be reported in accordance with Annex F.

## 8.5.4 Design development

### 8.5.4.1 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

#### 8.5.4.2 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.

### 8.5.5 Components guidelines

For standard electric propulsion components, subclause 7.5.8 is applicable.

Specific components for electric propulsion are dealt with in the following subclauses of this subclause 8.5.

### 8.5.6 Thrusters

#### 8.5.6.1 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 8.1.

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

#### 8.5.6.2 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.

#### 8.5.6.3 Thrust modulation

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

#### 8.5.6.4 Thrust mismatch

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

#### 8.5.6.5 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.

#### 8.5.6.6 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.

#### 8.5.6.7 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 due to these parameters.

#### 8.5.6.8 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.

#### 8.5.6.9 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.

c. Reporting shall be in accordance with Annex E.

#### 8.5.6.10 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.

### 8.5.7 Thrust-vector control

#### 8.5.7.1 Devices for thrust-vector control

Devices used for thrust-vector control shall be

a. actively controlled pointing mechanisms supporting the thruster, as explained in 8.5.7.2 below; or

b. thrust-vector steering solutions within the thruster itself, as explained in 8.5.7.3 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.

#### 8.5.7.2 Thruster orientation mechanism

For the design of thruster orientation mechanisms for electric propulsion, subclause 7.5.18 of this Standard shall be applied.

#### 8.5.7.3 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.

### 8.5.8 Propellant management assembly

#### 8.5.8.1 General

In this subclause 8.5.8 the components of the propellant management assembly are listed and particular design drivers are addressed for components particular to electric propulsion systems.

#### 8.5.8.2 Standard components and fluids

a. For standard components of the propellant management assembly, subclause 7.5.8 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.

#### 8.5.8.3 Flow control unit

##### 8.5.8.3.1 General

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

8.5.8.3.2 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 8.5.8.3.1 into account.

#### 8.5.8.4 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.

#### 8.5.8.5 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.

#### 8.5.8.6 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.

#### 8.5.8.7 Propellant filters

For gas and liquid filters design, subclause 7.5.11 of this Standard shall be applied.

#### 8.5.8.8 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.

## 8.5.9 Propellant tanks

### 8.5.9.1 Reporting

The reporting shall be in accordance with Annex D.

### 8.5.9.2 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.

### 8.5.9.3 Liquid propellant tanks for electric propulsion systems

For tanks for electric propulsion systems using liquid propellants, subclause 7.5.16 of this Standard shall be applied.

### 8.5.9.4 Gaseous propellant tanks for electric propulsion systems

For tanks for electric propulsion systems using gaseous propellants (e.g. xenon), subclause 7.5.15 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.

## 8.5.10 Blow-down ratio

For electric propulsion systems working in blow-down mode (i.e. arcjets and resistojets), 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).

## 8.5.11 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).

## 8.5.12 Power supply, control and processing subsystem

### 8.5.12.1 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.

#### 8.5.12.2 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.

### 8.5.13 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.

### 8.5.14 Pyrotechnic devices

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

### 8.5.15 Ground support equipment (GSE)

#### 8.5.15.1 General

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

#### 8.5.15.2 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.

#### 8.5.15.3 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.

### 8.5.16 Contaminants

#### 8.5.16.1 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.)

#### 8.5.16.2 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.

### 8.5.17 Electrical design

#### 8.5.17.1 General

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

#### 8.5.17.2 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.

#### 8.5.17.3 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.

#### 8.5.17.4 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.

#### 8.5.17.5 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.

## 8.6 Physical

### 8.6.1 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.

### 8.6.2 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.

## 8.7 Verification

### 8.7.1 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 8.7, 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.

### 8.7.2 Verification by analysis

#### 8.7.2.1 General

For electric propulsion system, the following shall be applied:

a. subclause 7.6.2;

b. the additional subclauses of this subclause 8.7.2.

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 7.6.2. 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.

#### 8.7.2.2 Mutual effects of electrostatic and magnetic fields

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

#### 8.7.2.3 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.

#### 8.7.2.4 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.

#### 8.7.2.5 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.

c. The analyses specified in a. and b. shall be reported in accordance with Annex I.

### 8.7.3 Verification by test

#### 8.7.3.1 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.

#### 8.7.3.2 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.

#### 8.7.3.3 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.

#### 8.7.3.4 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.

#### 8.7.3.5 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.

f. The material properties specific for electric propulsion shall be reported according to Annex L.

#### 8.7.3.6 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.

#### 8.7.3.7 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.

### 8.7.4 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.

## 8.8 Quality factors

### 8.8.1 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.

### 8.8.2 Production and manufacturing

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

## 8.9 Operation and disposal

a. For operation and disposal, subclause 7.8 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.

## 8.10 Support

a. For deliverables, subclause 7.9 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 General

For the testing, cleaning, drying and disposal of propulsion systems, specific non-structural materials are used, such as propellants, pressurants, simulants and cleaning agents. This annex lists the supporting documents for the use, handling, storage and disposal of these materials.

## A.2 Propellants

### A.2.1 Storable propellants

CPIA Publication 194 Change 1 Chemical Rockets/Propellant Hazards, Vol. 3: Liquid Propellant Handling, Storage and Transportation.

IATA 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, Characterization of (except gun propellant)

### A.2.3 Liquid propellants

#### A.2.3.1 General

AFM 161-30 Chemical Rocket/Propellant Hazards, Vol. 2: Liquid Propellants

#### A.2.3.2 Hydrazine (N2H4)

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

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

#### A.2.3.3 Monomethylhydrazine (MMH)

MIL-PRF-27404C Propellant, Monomethylhydrazine

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

#### A.2.3.4 Nitrogen tetroxide (NTO) and mixed oxides of nitrogen (MON)

014.PS.002-01:1990 Propellant Specification Nitrogen Tetroxide (NTO) and Mixed Oxides of Nitrogen (MON-1/MON-3)

MIL-PRF-26539E Performance Specification Propellants, Nitrogen Tetroxide

NAS 3620-82 Nitrogen Tetroxide

TN-RT351-30/82 Propellant Specification Mixed Oxides of Nitrogen, Type

#### A.2.3.5 MON-1 and Type MON-3

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

#### A.2.3.6 Unsymetrical-dimethylhydrazine (UDMH)

MIL-PRF-25604E Propellant, Uns-dimethylhydrazine

#### A.2.3.7 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.2.3.8 Aerozine

KSC-STD-Z-0006 Aerozine-50

#### A.2.3.9 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

## A.3 Pressurants

DIN 32536 Argon

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 |
| MCS-SPC-C-20 | Water High Purity and Distilled, Specification for |
| MIL-C-81302D(1) | Cleaning, Compound, Solvent, Trichlorotrifluoroethane |

## A.5 Cleaning agents

| | |
|---|---|
| TT-I-735A(3) NOT 1 | Isopropyl Alcohol |
| BAe MS 1138 | Material Specification, Propan-2-ol, Isopropyl Alcohol (IPA), Special Grade |

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# Annex B (informative)

# Full table of contents

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# Annex C (normative)

# Propulsion performance analysis report (AR-P) DRD

## C.1 DRD identification

### C.1.1 Requirement identification and source document

ECSS-E-30 Part 5B, subclauses 4.3.2.1.a., 4.10.1.b.1., 5.6.4, 6.6.8, 7.5.2, 7.9.a. and 8.5.2.

### C.1.2 Purpose and objective

The objective of the propulsion performance analysis report is to analyse and establish the performance of a propulsion system, subsystem or component and establish a record of the evolution of the performance of a propulsion system, subsystem or component.

The AR-P is prepared on the basis of the applicable specifications and requirements documentation.

## C.2 Expected response

### C.2.1 Response identification

The requirements for document identification contained in ECSS-M-50 shall be applied to the analysis report propulsion performance (AR-P).

### C.2.2 Scope and content

The AR-P shall provide the information presented in the following sections:

**<1> Introduction**

The AR-P shall contain a description of the purpose, objective, content and the reason prompting its preparation.

**<2> Applicable and reference documents**

The AR-P shall list the applicable and reference documents in support to the generation of the document.

**<3> Terms, definitions, abbreviated terms and symbols**

(a) The AR-P shall use the terms, definitions, abbreviated terms and symbols used in ECSS-E-30 Part 5.

(b) The AR-P shall include any additional term, definition, abbreviation or symbol used.

**<4> General description of the propulsion system, subsystem or component**

(a) Overview

(1) The AR-P shall describe the propulsion system, subsystem or component and introduce its terminology.

(2) Reference shall be made to the applicable design definition file, inclusive its revision status.

(b) Coordinate systems

The AR-P shall describe the coordinate systems used in the propulsion system, propulsion subsystem or propulsion component.

**<5> Summary and understanding of the propulsion performance requirements**

(a) The AR-P shall list and summarize the parameters that are used to assess the performance of the propulsion component, subsystem or system.

(b) The AR-P shall include the discussion on the understanding and clarification of the requirements.

(c) The AR-P shall include the description of the reference conditions used for the analysis.

**<6> Analysis description**

(a) Assumptions, simplifications and models

Since analysis covers both model computations and elaboration of measurements, the AR-P shall cover:

(1) the description of the used assumptions,

(2) the description of simplifications, and

(3) a brief summary of rationale and software used for the propulsion performance analysis and the related uncertainties.

NOTE Uncertainties can result from numerical inaccuracies, measurement inaccuracies, models that are based on simplifications and the conditions under which data was obtained.

(b) Approach

(1) The AR-P shall include a description and a discussion of the analysis methodology; describing what is done and why.

(2) If experimental input data is used:

- the data sheet or test results shall be referenced or reproduced in the AR-P;
- the test plan, test procedures, individual test item descriptions, and existing deviations from the generic design on which the experimental data is based shall be referenced;
- a description of the test conditions shall be given in the AR-P.

(3) If data from modelling, not within the project, is used,

- the data shall be referenced or reproduced;
- the models from which this data results, shall be referenced.

(4) If modelling is used, the models shall be referenced and summarized.

(5) An estimate of the accuracy of the methodology shall be included in the AR-P.

(6) The AR-P shall include a justification and validation of the methodology, either in the AR-P itself, or by referenced documents.

(c) Calculations

The AR-P shall describe the calculations that are being made to obtain the propulsion performance parameters.

### <7> Discussion of results and comparison with requirements

(a) The AR-P shall include a discussion of the results in view of

* the accuracy of input data,
* the validation status of the computational methods and models used,
* deviations in test conditions and test items used to obtain experimental data, and
* the simplifications and assumptions used in the models and calculations.

(b) The AR-P shall include an assessment of the effects of the subjects given in section <7>(a) on the propulsion performance parameters.

(c) The AR-P shall include a comparison of the propulsion performance parameters with the requirements, taking into account the inaccuracies of the propulsion performance parameters, and deviations shall be commented in the AR-P.

(d) In case previous propulsion performance analyses are available, the AR-P shall include

* a comparison of the result of the present propulsion performance analysis with the previous ones, and
* a report including a discussion on the differences.

NOTE Requirements are not limited to system or subsystem requirements; they can also be "internal" or "derived" requirements.

### <8> Recommendations

The AR-P, based on the information given in section <7>, shall include a list with the following recommendations:

(a) suggestions for future work and additional investigations or improvements;

(b) feedback to improve the propulsion performance and propulsion performance analysis.

### <9> Summary and conclusions

In the AR-P a summary of the results shall be given containing the following information:

(a) a statement whether or not the objective has been achieved;

(b) limitations of the performed work.

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# Annex D (normative)

# Gauging analysis report (AR-G) DRD

## D.1 DRD identification

### D.1.1 Requirement identification and source document

ECSS-E-30 Part 5B, subclauses 6.6.6.1, 7.5.16, 7.6.2.2.f.2., 7.9.f. and 8.5.9.

### D.1.2 Purpose and objective

The objective of the gauging analysis report (AR-G) is to analyse and describe the gauging system of a propulsion system, subsystem and its performance.

The AR-G is prepared based on the applicable specifications and requirements documentation.

## D.2 Expected response

### D.2.1 Response identification

The requirements for document identification contained in ECSS-M-50 shall be applied to the gauging analysis report (AR-G).

### D.2.2 Scope and content

The AR-G shall provide the information presented in the following sections:

**<1> Introduction**

The AR-G shall contain a description of the purpose, objective, content and the reason prompting its preparation.

**<2> Applicable and reference documents**

The AR-G shall list the applicable and reference documents in support to the generation of the document.

**<3> Terms, definitions, abbreviated terms and symbols**

(a) The AR-G shall use the terms, definitions, abbreviated terms and symbols used in ECSS-E-30 Part 5.

(b) The AR-G shall include any additional term, definition, abbreviated term or symbol used.

**<4> General description of the measure and coordinate system for the gauging analysis**

(a) Overview

(1) The AR-G shall describe the gauging system or subsystem and introduce its terminology.

(2) Reference shall be made to the applicable design definition file, inclusive its revision status.

(b) Coordinate systems

The AR-G shall describe the coordinate systems used in the gauging system or subsystem.

**<5> Summary and understanding of the gauging requirements**

(a) The AR-G shall list and summarize the parameters that are used to describe the functioning of the gauging subsystem or system.

(b) The AR-G shall also include a discussion of the understanding and clarification of the requirements.

**<6> Analysis description**

(a) Assumptions, simplifications and models

Since analysis covers both model computations and elaboration of measurements, the AR-G shall cover

(1) the description of the used assumptions,

(2) the description of simplifications, and

(3) a brief summary of rationale and software used for the gauging analysis and the related uncertainties.

NOTE Uncertainties can result from numerical inaccuracies, measurement inaccuracies, models that are based on simplifications and the conditions under which data have been obtained.

(b) Approach

(1) The AR-G shall include a description and a discussion of the analysis methodology; describing what is done and why.

(2) If experimental input data is used:

- the data sheet or test results shall be referenced or reproduced in the AR-G;
- the test plan, test procedures, individual test item descriptions, and existing deviations from the generic design on which the experimental data is based shall be referenced;
- a description of the test conditions shall be given in the AR-G.

(3) If data from modelling, not within the project, is used:

- the data shall be referenced or reproduced;
- the models from which this data results, shall be referenced.

(4) If modelling is used, the models shall be referenced and summarized.

(5) An estimate of the accuracy of the methodology shall be included in the AR-G.

(6) The AR-G shall include a justification and validation of the methodology, either in the AR-G itself, or by referenced documents.

(c) Calculations

The AR-G shall describe the calculations that are being made to obtain the gauging performance.

### <7> Discussion of results and comparison with requirements

(a) The AR-G shall include a discussion of the results in view of:

* the accuracy of input data,
* the validation status of the computational methods and models used,
* deviations in test conditions and test items used to obtain experimental data, and
* the simplifications and assumptions used in the models and calculations.

(b) The AR-G shall include an assessment of the effects of the subjects of <7>(a) on the gauging performance.

(c) The AR-G shall include a comparison of the gauging performance with the requirements, taking into account the inaccuracies of the gauging performance parameters.

(d) In case previous gauging analyses are available, the AR-G shall include a comparison of the result of the present gauging analysis with the previous ones and a report discussing the differences.

NOTE Requirements are not limited to system or subsystem requirements; they can also be "internal" or "derived" requirements.

### <8> Recommendations

The AR-G, based on the information provided in section <7>, shall list the following recommendations:

(a) suggestions for future work and additional investigations or improvements (e.g. lessons learned, state-of-the-art);

(b) feedback to improve the gauging and gauging analysis.

### <9> Summary and conclusions

In the AR-G a summary of the results shall be given containing the following information:

(a) a statement whether or not the objective has been achieved;

(b) limitations of the performed work.

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# Annex E (normative)

# Addendum: Specific propulsion aspects for thermal analysis DRD

## E.1 DRD identification

### E.1.1 Requirement identification and source document

ECSS-E-30 Part 5B, subclauses 4.3.3.2.e.1.(b), 4.3.6.2.4.b.2., 4.3.8.6.c.2., 4.6.2.i., 4.6.3.1.j., 4.8.4.2.2.c., 4.10.1.b.2., 5.6.5.2.4.j., 5.6.5.4.16.b.2., 6.6.10.2.8.g., 6.6.10.4.7.f.2.(b), 6.6.14.12.3.e.2., 7.5.17.7.b., 7.6.2.2.b.2., 7.9.d., 8.3.3.b. and 8.5.6.9.c.,

### E.1.2 Purpose and objective

For the purpose and objectives of the thermal analysis DRD, see [Thermal analysis DRD].

This addendum specifies the additional information to be included in the thermal analysis DRD to analyze and describe the thermal aspects of a propulsion system, subsystem or component.

## E.2 Expected response

### E.2.1 Response identification

N/A

### E.2.2 Scope and content

In a thermal analysis of a propulsion system, subsystem, or component, additionally to the information specified in the DRDs in ECSS-E-30 Part 1, the following information shall be given:

**<1> General description of typical propulsion thermal aspects**

(a) The thermal analysis shall describe the thermal problems and aspects particularly related to propulsion and introduce its terminology.

NOTE Typical thermal aspects in propulsion are:

- Physical phenomena
  - Radiation cooling

— Regenerative cooling
— Heat-soak back
— Change in thermal characteristics (emissivity) due to deposition of sputtering material

- Hardware dedicated aspects
  — Thermal conditioning before operation
  — Thermal shock
  — Propellant evaporation
  — Propellant stratification
  — Thermal stresses in solid propellants
  — Thermal induced ageing / damage in solid propellants
  — Thermal conditions at the start
  — Heating of the nozzle and the nozzle throat
  — Bake-out / thermal cleaning
  — Thermal analysis for propellant feed systems,
  — Thermal stresses in radiation cooled nozzles
  — De-stratification
  — Thermo mechanical cycling.

(b) These information shall include reference to the applicable design definition files, inclusive their revision status

**<2> Summary and understanding of thermal aspects of propulsion systems**

(a) The thermal analysis shall describe the thermal aspect that is analysed and treated.

(b) The thermal analysis shall list and summarize the parameters that are used to describe the thermal behaviour and its related effects.

(c) The thermal analysis shall include a discussion on the understanding of the requirements, addressing how these requirements are being met.

(d) The thermal analysis shall include a discussion on the used assumptions, simplifications and possible experimental characterizations for materials that are subject to chemical change (e.g. pyrolysis of phenol resin).

**<3> Description of the propulsion thermal analysis**

(a) Assumptions, simplifications and models

Since analysis covers both model computations and elaboration of measurements, the thermal analysis shall cover

(1) the description of the used assumptions,

(2) the description of simplifications, and

(3) a brief summary of rationale and software used for the thermal analysis and the related uncertainties.

(b) Propulsion thermal aspects

The thermal analysis shall include a description and a discussion of the following thermal aspects that are typical for propulsion subsystems and systems:

(1) Thermal conditioning before operation

[a] the initial and final conditions of the thermal state of a propulsion system;

[b] how the thermal conditioning is realized

NOTE Thermal conditioning includes pre-heating of cathodes, neutralizers, feed systems, catalyst beds, propellants (e.g. xenon and cesium) and chill-down of cryogenic systems.

(2) Thermal shock

[a] how the thermal shock effects have been assessed;

[b] the demonstration that the propulsion component, subsystem or system can withstand the thermal shocks that are being encountered.

NOTE Thermal shocks occur during chill-down (from ambient temperatures to cryogenic temperatures, < 20 K) and start-up of propulsion systems (from ambient or cryogenic temperatures to temperatures often exceeding 3 000 K).

(3) Propellant evaporation

[a] the means by which it is ensured that the amount of propellant evaporation meets the specifications;

[b] the passive or active measures that have been or have to be implemented to satisfy the requirements.

NOTE Propellant evaporation is especially important for cryogenic propellants (boil-off) and for FEEP (evaporation and subsequent condensation of liquid metal).

(4) Propellant stratification

the measures by which it is ensured that the propellant stratification conforms to the requirements.

NOTE Propellant stratification especially occurs with cryogenic propellants where the temperature of the upper levels can be substantially higher than the temperature of the lower levels.

(5) Thermal stresses in solid propellants

[a] the analyses of the temperature, temperature gradients, and changes in temperature and temperature gradients after curing of a solid propellant grain;

[b] the thermal analyses of propellant grains that have been in orbit a long time (e.g. several months up to several years) before being ignited;

[c] how the resulting thermal stresses have been calculated;

[d] the evidence that the thermal history of the propellant grain does not introduce stresses that transgress the specified stresses (e.g. shrinkage).

NOTE 1 Curing of propellant grains usually takes place at temperatures well above the operational temperature of the propellant.

NOTE 2 De-orbiting motors may be in orbit for several years. During this period the solid motors may undergo many temperature changes (thermal cycles).

(6) Thermal induced aging and damage in solid propellants

[a] the evidence that the thermal induced aging of solid propellants conforms to the system and subsystem specifications;

[b] the evidence that for solid rocket motors that undergo many temperatures changes (thermal cycling) (e.g. thermally non-controlled de-orbiting motors that are a long time in space before being operated), the coupled thermal-mechanical computations demonstrate that damage to the propellant grain conforms to the system and subsystem specifications;

NOTE Aging of solid propellants is accelerated at high temperatures and by temperature cycling. This can especially be important for solid motors that are a long time in before being operated (e.g. de-orbiting motors).

(7) Radiation cooling

[a] the temperature management of propulsion components, subsystems or systems that are cooled by radiation;

NOTE Typical examples are mono- and bi-propellant thrusters and electric propulsion systems.

[b] the evidence that the propulsion component, subsystem or system temperature conforms to the component, subsystem or system requirements;

[c] the evidence that the radiation cooled propulsion components, subsystems or systems conform to the requirements when installed in a spacecraft or launcher where its view factors can have changed substantially, either due to its installation or by the installation of radiation shields.

(8) Regenerative cooling

[a] the evidence that the regenerative cooling:

- keeps the material temperatures within the boundaries specified by the requirements;
- keeps the temperature of the regenerative cooling fluid within the boundaries specified by the requirements.

NOTE Some rocket engine cycles (e.g. expander cycle, bleed cycle) strongly rely on a proper energy transfer to the cooling fluid.

[b] the evidence that thermal expansion and contraction conform to the structural requirements.

(9) Heat soak-back

the evidence that after shutdown of a propulsion subsystem or system the temperature of cold structures of the propulsion subsystem or system and the temperature of structural elements close to the propulsion subsystem or system conform to the subsystem or system requirements.

NOTE After shutdown of a rocket engine, there is no active cooling any more, and also cooling of parts and components that are normally cooled by the propellant flow is interrupted. Therefore parts that during the operation of the propulsion system remain cool, heat up mainly due to conduction and radiation.

(10) Thermal conditions at the start

[a] the thermal analyses that have been made to establish the thermal conditions before the starting of a rocket motor;

[b] measurements to be according to the thermal analysis in order to establish the thermal state of the engine.

NOTE 1 If regenerative or film-cooled rocket motors are (re)started while hot, it can be impossible to establish a proper regenerative coolant flow (flow blockage) or to establish an appropriate coolant film. In that case, measures have to be taken to ensure that the proper coolant flow is established or measures have to be taken that prevent the motor from being restarted.

NOTE 2 In particular for cryogenic upper stage engines, starting the engine at too low temperatures can lead to combustion instability or insufficient power delivery from the regenerative cooling circuit for expander cycle engines.

(11) Heating of the nozzle and the nozzle throat

[a] the thermal analyses for the nozzle and its components e.g. throat-inserts, flexible seal, thermal / ablative materials, temperature gradients and related stresses in regeneratively cooled nozzles;

[b] the selection of high temperature materials that are compatible with the environment (composition of the exhaust gases);

[c] the associated thermal expansion / contraction, the induced thermal stresses and the effect on clearances.

[d] the evidence that the nozzle and nozzle throat meet the subsystem and system thermal requirements.

NOTE The highest heat transfer in rocket motors is encountered in the throat region. During start-up the nozzle encounters thermal shocks and strong transient thermal effects.
Nozzles of cryogenic systems undergo a thermal shock and cooling down to cryogenic temperatures. Typical stagnation temperatures of the combustion products exceed 3 000 K.

(12) Change in thermal characteristics (emissivity) due to deposition of sputtering material

[a] the effects of the change in irradiative properties of electric propulsion systems due to deposition of sputtering material during long term testing in vacuum chambers;

[b] the measures to be taken to ensure that notwithstanding a changing thermal behaviour of the electric propulsion system during long term testing, the tests remain representative for the performance of an electric propulsion system in flight.

NOTE During long term testing of an electric propulsion system in a vacuum chamber, coating material from the walls of the vacuum chamber can be deposited on the electric propulsion system. This

can cause a change in the thermal characteristics of the electric propulsion system during long term testing.

(13) Bake-out / thermal cleaning

the thermal analysis and temperature evolution of electric propulsion thrusters for bake-out or thermally cleaning these thrusters.

NOTE The cleansing of contaminants (e.g. FEEP) of electric propulsion thrusters, to ensure a proper operation, is done by heating the thrusters to high temperatures. These temperatures usually exceed the operational temperature of the electric propulsion thrusters and can be design drivers.
Other electric propulsion thrusters may be heated to melt or evaporate particulate material from the grids.

(14) Thermal analysis for propellant feed systems

the thermal analysis and temperature control to maintain the propellant feed system within its specified temperature range.

NOTE 1 The propellants are delivered to the thrusters / motors / engines within a specified temperature range.

NOTE 2 For some propellants there is the danger of freezing ($N_2H_4$) or liquefaction (xenon).

NOTE 3 For some propellants there can be a danger of flow blockage or of explosion due to adiabatic compression of propellant vapours during priming.

(15) Thermal stresses in radiation cooled nozzles

the structure of a radiation cooled nozzle or nozzle section can withstand the combination of stresses due to internal pressure, external loads and thermal stresses

NOTE 1 Radiation cooled nozzles are often found on satellite engines and attitude control thrusters.

NOTE 2 Some large rocket engines have a nozzle extension that is radiation cooled.

(16) De-stratification

the evidence that the amount of usable cryogenic propellant conforms to the requirements when sloshing or rolling of the stage is taken into account.

NOTE If cryogenic propellant with high temperatures (that is normally at the top of the tank) due to sloshing would enter the propellant feed lines, the entrance conditions for the propellant pump may no longer be satisfied.

(17) Thermo-mechanical cycling

[a] the evidence that engine life requirements are met for the number of thermal cycles the engine undergoes;

[b] the demonstration that crack propagation conforms to the engine requirements.

NOTE 1 Thermo mechanical cycling is especially important for reusable liquid engines.

NOTE 2 Thermo mechanical cycling can be important for engines during development testing.

NOTE 3 Crack propagation and crack growth due to thermo-mechanical cycling can especially be important for engines built with a tubular structure for regenerative cooling.

### <4> Calculations

The thermal analysis shall describe the calculations that are being made to assess the thermal effects on a propulsion subsystem or system.

### <5> Discussion of results and comparison with requirements

(a) The thermal analysis shall include a discussion of the results in view of:

* the accuracy of input data,
* the validation status of the computational methods and models used,
* deviations in test conditions and test items used to obtain experimental data, and
* the simplifications and assumptions used in the models and calculations.

(b) The thermal analysis shall include an assessment of the effects of the subjects mentioned in subclause <5>(a) on the parameters used to describe the thermal behaviour, and the results .

(c) The thermal analysis shall include a comparison of the parameters used to describe and results with the requirements, taking into account the inaccuracies of the parameters.

(d) In case previous thermal analyses are available, the thermal analysis shall include a comparison of the result of the present thermal analysis with the previous ones and a report with the differences.

### <6> Recommendations

The thermal analysis, based on subclause <4> shall include a list with the following recommendations:

(a) suggestions for future work and additional investigations or improvements, (e.g. lessons learned, state-of-the-art);

(b) feedback to improve the thermal analysis.

### <7> Summary and conclusions

The thermal analysis shall include a summary of the results and an assessment of the limitations of the performed work.

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# Annex F (normative)

# Plume analysis report (AR-Pl) DRD

## F.1 DRD identification

### F.1.1 Requirement identification and source document

ECSS-E-30 Part 5B, subclauses 5.5.c.NO TAG, 7.5.3.2.b.c., .7.5.5b.c., 7.6.2.2.e.5., 7.9.e., 8.2.3.a.b., 8.3.1.b. and 8.5.3.2.b.c.

### F.1.2 Purpose and objective

The objective of the plume analysis report (AR-Pl) is to analyse and describe the plume, e.g. shape, structure, composition, electromagnetic properties, particulate trajectories, of a propulsion system or subsystem.

The AR-Pl is prepared based on the applicable specifications and requirements documentation.

## F.2 Expected response

### F.2.1 Response identification

The requirements for document identification contained in ECSS-M-50 shall be applied to the plume analysis report (AR-Pl).

### F.2.2 Scope and content

The AR-Pl shall provide the information presented in the following sections:

**<1> Introduction**

The AR-Pl shall contain a description of the purpose, objective, content and the reason prompting its preparation.

**<2> Applicable and reference documents**

The AR-Pl shall list the applicable and reference documents in support to the generation of the document.

**<3> Terms, definitions, abbreviated terms and symbols**

(a) The AR-Pl shall use the terms, definitions, abbreviated terms and symbols used in ECSS-E-30 Part 5.

(b) The AR-Pl shall include any additional term, definition, abbreviated term or symbol used.

### <4> General description

(a) Overview

(1) The AR-Pl shall describe the plume and the plume parameters and introduce their specific terminology.

(2) Reference shall be made to the applicable design definition file, inclusive its revision status and the applicable study requirements.

(b) Coordinate systems

The AR-Pl shall describe the coordinate systems used in the plume analysis.

### <5> Summary and description of the plume

(a) The AR-Pl shall list and summarize the parameters that are used to describe the plume.

(b) The AR-Pl shall also include a discussion on the understanding and clarification of the requirements.

(c) The AR-Pl shall include the description of the reference conditions used for the analysis.

### <6> Analysis of the plume

(a) Assumptions, simplifications and models

Since analysis covers both model computations and elaboration of measurements, the AR-Pl shall cover:

(1) the description of the used assumptions,

(2) the description of the boundary conditions,

(3) the description of simplifications,

(4) the description of, or reference to diagnostic systems used in tests in case test results are used, and

(5) a brief summary and justification of rationale and software used for the plume analysis and the related uncertainties.

NOTE Uncertainties can be due to numerical inaccuracies, measurement inaccuracies, models that are based on simplifications and the conditions under which data have been obtained.

(b) Approach

(1) The AR-Pl shall include a description and a discussion of the analysis methodology describing what is done and why.

(2) If experimental input data is used:

- the data sheet or test results shall be referenced or reproduced in the AR-Pl;
- the test plan, test procedures, individual test item descriptions, and existing deviations from the generic design on which the experimental data is based shall be referenced;
- a description of the test conditions shall be given in the AR-Pl.

(3) If data from modelling, not within the project, is used:

- the data shall be referenced or reproduced;
- the models from which this data results, shall be referenced and a discussion of these models included.

(4) If modelling is used, the models shall be referenced and summarized.

(5) An estimate of the accuracy of the methodology shall be included in the AR-Pl.

(6) The AR-Pl shall include a justification and validation of the methodology, including tools and methods, validated, either in the AR-Pl itself, or by referenced documents.

(7) The AR-Pl shall provide evidence that models are used within their validity range.

### <7> Calculations

The AR-Pl shall describe the calculations that are being made to assess the plume.

### <8> Discussion of results

(a) The AR-Pl shall include a discussion of the results taking into account:

* the accuracy of input data,
* the validation status of the computational methods and models used,
* the deviations in test conditions and test items used to obtain experimental data, and
* the simplifications and assumptions used in the models and calculations.

(b) The AR-Pl shall include the assessment of the effects of the subjects mentioned in <8>(a) on the results.

(c) In case previous plume analyses for the same project are available, the comparison between the result of the present plume analysis with the previous ones, and the differences shall be reported.

### <9> Recommendations

In the AR-Pl, based on the information given in <8>, a list of the following recommendations shall be given:

(a) suggestions for future work and additional investigations or improvements, (e.g. lessons learned, state-of-the-art);

(b) feedback to improve the plume analysis.

### <10> Summary and conclusions

In the AR-Pl a summary of the results shall be given containing the following information:

(a) a summary of the main results;

(b) limitations of the performed work.

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# Annex G (normative)

# Nozzle and discharge flow analysis report (AR-N) DRD

## G.1 DRD identification

### G.1.1 Requirement identification and source document

ECSS-E-30 Part 5B, subclauses 7.6.2.2.e.2., 4.3.3.2.j., 4.6.2.e.2., 4.10.1.b.6., 5.6.3.1, 6.4.5.b., 6.6.8.5.b., 6.6.8.6.1., and 6.6.8.7.1.

### G.1.2 Purpose and objective

The objective of the nozzle and discharge flow analysis report is to analyse and describe the nozzle and discharge flow of a propulsion subsystem or system in view of e.g. life-time, particle impingement, erosion, flow separation, the occurrence of shocks, heat transfer, performance assessment, and plasma characteristics.

The AR-N is prepared based on the applicable specifications and requirements documentation.

## G.2 Expected response

### G.2.1 Response identification

The requirements for document identification contained in ECSS-M-50 shall be applied to the AR-N.

### G.2.2 Scope and content

The AR-N shall provide the information presented in the following sections:

<1> **Introduction**

The AR-N shall contain a description of the purpose, objective, content and the reason prompting its preparation.

<2> **Applicable and reference documents**

The AR-N shall list the applicable and reference documents in support to the generation of the document.

## <3> Terms, definitions, abbreviated terms and symbols

(a) The AR-N shall use the terms, definitions, abbreviated terms and symbols used in ECSS-E-30 Part 5.

(b) The AR-N shall define any additional term, abbreviated term or symbol used.

## <4> General description

(a) Overview

(1) The AR-N shall describe the nozzle and discharge flow and introduce its terminology.

(2) The AR-N shall list those parameters that are important for this analysis and explain their meaning, use and relevance.

(3) Reference shall be made to the applicable design definition file, inclusive its revision status.

(b) Coordinate systems

The AR-N shall describe the coordinate systems used in the nozzle-discharge system.

## <5> Summary and description of the nozzle and the nozzle discharge flow

(a) The AR-N shall include and summarize the parameters that are used to describe the nozzle / discharge flow.

(b) The AR-N shall include a discussion on the understanding and clarification of the requirements.

(c) The AR-N shall include the description of the reference conditions used for the analysis.

## <6> Analysis description

(a) Assumptions, simplifications and models

Since analysis covers both model computations and elaboration of measurements, the AR-N shall cover:

(1) the description of the physical models used in the analysis,

(2) the description of the used assumptions,

(3) the description of the boundary conditions,

(4) the description of simplifications,

(5) the description of, or reference to the diagnostic systems used in tests in case test results are used, and

(6) a brief summary and justification of rationale and software used for the nozzle / discharge flow analysis and the related uncertainties.

NOTE Uncertainties can be due to numerical inaccuracies, measurement inaccuracies, models that are based on simplifications and the conditions under which data have been obtained.

(b) Approach

(1) The AR-N shall include a description and a discussion of the analysis methodology, describing what is done and why.

(2) If experimental input data is used:

- the data sheet or test results shall be referenced or reproduced in the AR-N;

- the test plan, test procedures, individual test item descriptions, and existing deviations from the generic design on which the experimental data is based shall be referenced;
- a description of the test conditions shall be given in the AR-N

(3) If data from modelling, not within the project, is used:

- the data shall be referenced or reproduced;
- the models from which this data results, shall be referenced and a discussion of these models shall be included.

(4) If modelling is used, the models shall be referenced and summarized.

(5) An estimate of the accuracy of the methodology shall be included in the AR-N.

(6) The AR-N shall provide evidence that the models are used in their validity range.

(7) The AR-N shall include a justification and validation of the methodology, including tools and models, either in the AR-N itself, or by referenced documents.

### <7> Calculations

The AR-N shall describe the calculations that are being made to assess the nozzle and discharge flow.

### <8> Discussion of results and comparison with requirements

(a) The AR-N shall present a discussion of the results in view of:

* the accuracy of input data,
* the validation status of the computational methods and models used,
* the deviations in test conditions and test items used to obtain experimental data, and
* the simplifications and assumptions used in the models and calculations.

(b) The AR-N shall include the assessment of the effects on the results of the subjects mentioned in <8>(a).

(c) The AR-N shall include a comparison of the results with the requirements taking into account the inaccuracies of the parameters.

(d) In case previous nozzle and discharge flow analyses for the same project are available, the comparison of the result of the present nozzle and discharge flow analysis with the previous ones shall be included, and the differences shall be reported.

### <9> Recommendations

In the AR-N, based on the information provided in <7>, a list of the following recommendations shall be given:

(a) suggestions for future work and additional investigations or improvements (e.g. lessons learned, state-of-the-art);

(b) feedback to improve the nozzle and discharge flow analysis.

### <10> Summary and conclusions

In the AR-N a summary of the results shall be given containing the following information:

(a) a summary of the main results;

(b) limitations of the performed work.

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# Annex H (normative)

# Sloshing analysis report (AR-S) DRD

## H.1 DRD identification

### H.1.1 Requirement identification and source document

ECSS-E-30 Part 5B, subclause 4.6.2.e.3., 6.6.6.7.b., 7.6.2.3.3.c. and 7.9.c.

### H.1.2 Purpose and objective

The objective of the sloshing analysis report (AR-S) is to analyse and describe the sloshing in a propulsion system or subsystem, with the objective to e.g. design baffles in a tank, design the PMD, provide input data for coupled analysis with the control system, evaluate the proper functioning of and the effects of sloshing on the propulsion system.

The AR-S is prepared on the basis of the applicable specifications and requirements documentation.

## H.2 Expected response

### H.2.1 Response identification

The requirements for document identification contained in ECSS-M-50 shall be applied to the AR-S.

### H.2.2 Scope and content

The AR-S shall provide the information presented in the following sections:

**<1> Introduction**

The AR-S shall contain a description of the purpose, objective, content and the reason prompting its preparation.

**<2> Applicable and reference documents**

The AR-S shall list the applicable and reference documents in support to the generation of the document.

**<3> Terms, definitions, abbreviated terms and symbols**

(a) The AR-S shall use the terms, definitions, abbreviated terms and symbols used in ECSS-E-30 Part 5.

(b) The AR-S shall include any additional term, definition, abbreviated term or symbol used.

## <4> General description

(a) Overview

(1) The AR-S shall describe the analysed sloshing problem and introduce its terminology.

(2) The AR-S shall list those parameters that are important for the analysis and explain their meaning, use and relevance,

(3) Reference shall be made to the applicable design definition file, inclusive its revision status.

(b) Coordinate systems

The AR-S shall describe the coordinate systems used in the propulsion system or subsystem for which a sloshing analysis is made.

## <5> Summary and description of sloshing

(a) The AR-S shall describe the sloshing and the effects sloshing can have on propulsion subsystems and systems.

(b) The AR-S shall list and summarize the parameters, inclusive dimensionless numbers, that are used to describe sloshing and its related effects.

(c) The AR-S shall include a discussion on the understanding and clarification of the requirements.

## <6> Description of the sloshing analysis

(a) Assumptions, simplifications and models

Since analysis covers both model computations and elaboration of measurements, the AR-S shall include:

(1) the description of the used assumptions,

(2) the initial and boundary conditions used in the analysis,

(3) the description of simplifications, and

(4) a brief summary and justification of rationale and software used for the sloshing analysis and the related uncertainties.

NOTE Uncertainties can be due to numerical inaccuracies, measurement inaccuracies, models that are based on simplifications and the conditions under which data have been obtained.

(b) Approach

(1) The AR-S shall include a description and a discussion of the analysis methodology; describing what is done and why.

(2) If experimental input data is used:

- the data sheet or test results shall be referenced or reproduced in the AR-S;
- the test plan, test procedures, individual test item descriptions, and existing deviations from the generic design on which the experimental data is based shall be referenced;
- a description of the test conditions shall be given in the AR-S.

(3) If data from modelling, not within the project, is used:

- the data shall be referenced or reproduced;
- the models from which this data results, shall be referenced.

(4) If modelling is used, the models shall be referenced and summarized.

(5) An estimate of the accuracy of the methodology shall be included in the AR-S.

(6) The AR-S shall include a justification and validation of the methodology, either in the AR-S itself, or by referenced documents.

### <7> Calculations

The AR-S shall describe the calculations that are being made to assess the sloshing, e.g. history of the liquid position, local and global torques and forces, and thermal effects.

### <8> Discussion of results and comparison with requirements

The AR-S shall include:

(a) a discussion of the results in view of:

* the accuracy of input data,
* the validation status of the computational methods and models used,
* the deviations in test conditions and test items used to obtain experimental data, and
* the simplifications and assumptions used in the models and calculations;

(b) the assessment of the effects of the subjects mentioned in <8>(a) on the sloshing behaviour;

(c) a comparison of the results with the requirements, taking into account the inaccuracies of the parameters, and the deviations shall be commented;

(d) a discussion on the generated local and global forces and torques;

(e) in case previous sloshing analyses for the same project are available, a comparison of the result of the present sloshing analysis with the previous ones and a report on the differences;

(f) a discussion on the effects of sloshing on the propulsion subsystem or system.

### <9> Recommendations

In the AR-S, based on the information provided in <7> a list containing the following recommendations shall be given:

(a) suggestions for future work and additional investigations or improvements (e.g. lessons learned, state-of-the-art);

(b) feedback to improve the sloshing analysis.

### <10> Summary and conclusions

In the AR-S a summary of the results shall be given containing the following information:

(a) a summary of the main results;

(b) limitations of the performed work.

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# Annex I (normative)

# Propulsion transients analysis report (AR-Tr) DRD

## I.1 DRD identification

### I.1.1 Requirement identification and source document

ECSS-E-30 Part 5B, subclauses 4.3.8.6.e., 4.6.2.e.1., 4.10.1.b.5., 5.6.4.5.2, 6.6.8.9.1, 6.6.10.2.5.c., 6.6.10.3.2.d., 6.6.10.4.7.c.4., 7.5.1.5.b., 7.6.2.3.1.a., 7.9.b., 8.5.1.5.b. and 8.7.2.5.c.

### I.1.2 Purpose and objective

The objective of the propulsion transients analysis report (AR-Tr) is to analyse and describe the transient operations of a propulsion system or subsystem, e.g. ignition, chill-down, shut-down, effects of valve opening and closing (e.g. water-hammer effect and adiabatic compression), cross-talk between thrusters, start-up and shut-down of turbo-machinery, and system priming.

The AR-Tr is prepared based on the applicable specifications and requirements documentation.

## I.2 Expected response

### I.2.1 Response identification

The requirements for document identification contained in ECSS-M-50 shall be applied to the AR-Tr.

### I.2.2 Scope and content

The AR-Tr shall provide the information presented in the following sections:

**<1> Introduction**

The AR-Tr shall contain a description of the purpose, objective, content and the reason prompting its preparation.

**<2> Applicable and reference documents**

The AR-Tr shall list the applicable and reference documents in support to the generation of the document.

## <3> Terms, definitions, abbreviated terms and symbols

(a) The AR-Tr shall use the terms, definitions, abbreviated terms and symbols used in ECSS-E-30 Part 5.

(b) The AR-Tr shall include any additional term, definition, abbreviated term and symbol used.

## <4> General description of the transient operation analysis

(a) Overview

(1) The AR-Tr shall describe the relevant transient operations and introduce its terminology.

(2) Reference shall be made to the applicable design definition file, inclusive its revision status and the specific study requirements.

(b) Coordinate systems

The AR-Tr shall describe the coordinate systems used in the propulsion system or subsystem for which a transient analysis is made.

## <5> Summary and understanding of transient operations of propulsion systems and subsystems

(a) If the AR-Tr is split in several volumes, each volume shall clearly cross-reference the other volumes, including their revision status and relation to the applicable design definition file.

(b) The AR-Tr shall include:

(1) a description of the operations,

(2) a list and a summary of the parameters that are used to describe transient operations and their related effects, and

(3) a discussion of the understanding and clarification of the requirements.

(c) The AR-Tr shall include the description of the reference conditions used for the analysis.

## <6> Description of the transient analysis

(a) Assumptions, simplifications and models

Since analysis covers both model computations and elaboration of measurements, the AR-Tr shall include:

(1) the description of the used assumptions,

(2) the description of the initial and boundary conditions,

(3) the description of simplifications, and

(4) a brief summary and justification of rationale and software used for the transient analysis and the related uncertainties.

NOTE Uncertainties can be due to numerical inaccuracies, measurement inaccuracies, models that are based on simplifications and the conditions under which data have been obtained.

(b) Approach

(1) The AR-Tr shall include a description and a discussion of the analysis methodology; describing what is done and why.

(2) If experimental input data are used:

- the data sheet or test results shall be referenced or reproduced in the AR-Tr;

- the test plan, test procedures, individual test item descriptions, and existing deviations from the generic design on which the experimental data is based shall be referenced.
- a description of the test conditions shall be given in the AR-Tr.

(3) If data from modelling, not within the project, is used:

- the data shall be referenced or reproduced;
- the models from which this data results shall be referenced and a discussion of these models included.

(4) If modelling is used, the models shall be referenced and summarized.

(5) The AR-Tr shall provide evidence that models are used within their validity range,

(6) An estimate of the accuracy of the methodology shall be included in the AR-Tr.

(7) The AR-Tr shall include a justification and validation of the methodology, including tools and models, either in the AR-Tr itself, or by referenced documents.

### <7> Calculations

The AR-Tr shall describe the calculations that are being made to assess the transient effects on a propulsion subsystem or system.

### <8> Discussion of results and comparison with requirements

(a) The AR-Tr shall include a discussion of the results in view of:

* the accuracy of input data,
* the validation status of the computational methods and models used,
* the deviations in test conditions and test items used to obtain experimental data, and
* the simplifications and assumptions used in the models and calculations.

(b) The AR-Tr shall include an assessment of the effects on the results of the subjects mentioned in <8>(a).

(c) The AR-Tr shall include a comparison of the parameters with the requirements, taking into account the inaccuracies of the parameters.

(d) In case previous propulsion transients' analyses are available, the AR-Tr shall include a comparison of the result of the present transient analysis with the previous ones and a report on the discussion of the differences.

### <9> Recommendations

In the AR-Tr, based on the information given in <8>, a list including the following recommendations shall be given:

(a) suggestions for future work and additional investigations or improvements (e.g. lessons learned, state-of-the-art);

(b) feedback to improve the transient analysis.

### <10> Summary and conclusions

In the AR-Tr a summary of the results shall be given containing the following information:

(a) a summary of the main results;

(b) limitations of the performed work.

# Annex J (normative)

# Propulsion subsystem or system user manual (UM) DRD

## J.1 DRD identification

### J.1.1 Requirement identification and source document

ECSS-E-30 Part 5B, subclause 7.9.h. and 4.10.1.c.

### J.1.2 Purpose and objective

The objective of the user manual (UM) is to provide the instructions and procedures for the use of a propulsion system or subsystem.

The UM is prepared based on the applicable specifications and requirements documentation.

## J.2 Expected response

### J.2.1 Response identification

The requirements for document identification contained in ECSS-M-50 shall be applied to the UM.

### J.2.2 Scope and content

The UM shall provide the information presented in the following sections:

**<1> Introduction**

The UM shall contain a description of the propulsion system, purpose, objective, content and the reason prompting its preparation.

**<2> Applicable and reference documents**

The UM shall list the applicable and reference documents in support to the generation of the document.

**<3> Terms, definitions, abbreviated terms and symbols**

(a) The UM shall use the terms, definitions, abbreviated terms and symbols used in ECSS-E-30 Part 5.

(b) The UM shall include any additional term, definition, abbreviated term or symbol used.

### <4> Summary and understanding of the user manual

(a) Overview

(1) The UM shall include and summarize the activities covered in it and introduce its terminology.

(2) The UM shall include a discussion of the understanding and clarification of the requirements

(3) Reference shall be made to the applicable design definition file, inclusive its revision status.

(4) If the UM is split into several volumes, each volume shall clearly cross-reference the other volumes, including their revision status and relation to the applicable design definition file.

(b) Coordinate systems

The UM shall describe the coordinate systems used in the propulsion system or subsystem.

### <5> Activities during mission life

(a) Delivery

(1) The UM shall describe all technical activities that are related to the delivery of the propulsion system or subsystem.

(2) The UM shall include a recommendation that at least one copy of the UM is delivered with the hardware.

(b) Unpacking and packing

(1) The UM shall describe the technical activities for unpacking, the conditions to be met during unpacking, the precautions and safety procedures to be implemented when unpacking the propulsion system or subsystem.

(2) If packaging material is maintained for reuse, the UM shall describe the handling and storage of packaging material.

(3) The UM shall describe the technical activities for packing, the conditions under which packing shall take place, the precautions and safety procedures to be implemented during packing of the propulsion system or subsystem and the installation and activation of special recording, measurement or conditioning systems (e.g. temperature and shock registration, pressurized containers, and relative humidity).

(4) The UM shall describe the packaging materials, tools and special devices to be used (e.g. pressurization equipment).

(c) Incoming inspection

The UM shall:

(1) summarize the incoming inspection activities, and

(2) refer to the applicable incoming inspection procedures.

(d) Storage and maintenance

The UM shall:

(1) describe the conditions under which the propulsion system or subsystem can be stored and maintained during storage;

(2) address specific storage conditions (e.g. pressurized containers, relative humidity, grounding, cleanroom conditions, tempera-

ture controlled conditions, and measurements during storage) and the position in which the items are to be stored;

(3) describe operations to perform during storage (e.g. changing the position of a solid motor periodically), describing measures that ensure that items do not exceed the maximum storage time and procedures in case this time is nevertheless exceeded;

(4) include requirements for the storage conditions to meet the local safety regulations;

(5) list all activities to be performed in order to maintain the propulsion subsystem or system in a good condition (e.g. rotating turbo-machinery periodically to avoid sticking of seals).

(e) De-storage

The UM shall :

(1) describe the conditions under which the propulsion subsystem or system can be taken out of storage, and

(2) specifically describe the

- tools and equipment to be used,
- safety measures to be implemented,
- operations to be performed, and
- disposal of specific storage equipment.

(f) Integration and installation

The UM shall describe:

(1) the procedures, the precautions, the safety procedures to be implemented and the conditions (e.g. humidity, cleanroom, temperature) under which integration activities of the propulsion subsystems and systems or installation of the propulsion system in the satellite, spacecraft or stage shall take place;

(2) the procedures and the order of integration or installation if the propulsion subsystem or system is delivered in several parts;

(3) all interfaces with the propulsion subsystem or system.

(g) Ground operation

The UM shall describe:

(1) the conditions under which the propulsion subsystem or system can be operated, including mechanical and electrical procedures, and special procedures for priming;

(2) limitations of the propulsion subsystem or system;

(3) the applicable operational procedures for the propulsion subsystem or system;

(4) under what conditions refurbishment after ground operations is required and describe the procedures for refurbishment;

(5) the safety measures for the operation of the propulsion subsystem or system.

NOTE 1 In special cases the propulsion subsystem or system may be operated to obtain information not pertaining to the propulsion subsystem or system itself.

NOTE 2 The lifetime of a propulsion subsystem or system may be subject of the analysis report performance (AR-P).

(h) Tests and verification

(1) The UM shall list all activities that are related to testing and verifying integrated propulsion subsystems or systems, according to the AIV, test procedure and test specification in accordance to ECSS E-10-02.

(2) The activities specified in (1) above shall be summarized and cross-referenced.

(3) The UM shall summarize and cross-refer the verification activities performed according to the verification control document (ECSS-E-10-02).

(4) The UM shall include the tests to be performed.

(5) The UM shall include the verification activities to be performed, when these verification activities are required and the conditions to perform them.

NOTE The lifetime of a propulsion subsystem or system can be subject of the analysis report performance (AR-P).

(i) Handling

The UM shall list:

(1) the permitted handling conditions (e.g. change of orientation, position, deposition),

(2) the limiting conditions for handling (e.g. shocks, environmental conditions),

(3) where the handling forces can be applied on the propulsion subsystem or system,

(4) the protective measures to be implemented, and

(5) the safety measures to be implemented.

NOTE Handling is the moving (translation or rotation) of a propulsion subsystem or system when it is not in a container or integrated in a system (e.g. spacecraft, satellite, launcher).

(j) Transport

The UM shall include:

(1) the conditions under which the propulsion subsystem or system can be transported (e.g. orientation and environmental conditions);

(2) the limiting conditions for transport (e.g. shock, temperature, humidity, vibrations and duration of vibrations),

(3) the packaging to be used for transport in view of the transport itself (e.g. internal transport at the manufacturers plant, transport by truck, ship or plane);

(4) the installation of measuring and recording equipment;

(5) the special measures on the propulsion subsystem or system (e.g. prevention of rotation of turbo-machinery, and closing of nozzle);

(6) the conditions under which the propulsion subsystem or system can be transported once it has been integrated in a spacecraft, satellite, stage or launcher;

(7) the case that the tanks are loaded and the orientation of the launcher undergoes changes (e.g. from horizontal to vertical).

(k) Loading and unloading

For propulsion systems other than solid, the UM shall describe:

(1) the cases for loading and unloading the propulsion subsystem or system;

(2) the loading and unloading procedures for every case (e.g. ground tests, satellite loading, loading on the launcher, and related unloading);

(3) the safety measures to be implemented during loading and unloading;

(4) the conditions under which loading and unloading can take place;

(5) the disposal of unloaded fluids;

(6) the equipment to be used during loading and unloading;

(7) all measurements during loading and unloading;

(8) any limitation for the number of loading and unloading cycles the propulsion subsystem or system can undergo;

(9) the maximum duration for propellants and working fluids to remain loaded in the propulsion subsystem or system;

(10) measures that prevent contamination of the propulsion system during loading and unloading; and

(11) in case of unloading, which components cannot be reused and be replaced.

NOTE As solid propellants are usually present in the delivered propulsion subsystem or system they are not considered in this clause.
Loading of the propulsion subsystem or system comprises filling the tanks of the propulsion subsystem or system with propellants and working fluids (e.g. water, helium, nitrogen).

(l) Pre-launch and launch activities

The UM shall list:

(1) all activities to ensure that the propulsion system conforms to the requirements, describing at what stage of the pre-launch and launch sequence the activities shall be done.

NOTE These activities can include e.g. chill-down, pre-heating, topping-up of tanks, arming safe and arm devices, thermal conditioning, tank pressure measurements, and valve activation.

(2) the measures to be taken if the propulsion system does not conform to the requirements;

(3) the measures to put the propulsion system in a safe condition in case of a launch abort;

(4) all measures to recover the propulsion system for later use after a launch abort.

(m) In-orbit operation

(1) The UM shall describe all the activities for the propulsion system during the coast- or transfer-phase.

(2) The UM shall describe:

- all the activities that verify that the propulsion system is in a proper condition to be activated and operated;

- the measures to control the status of the propulsion system and to bring it in a proper condition to be activated and operated;
- the means to identify the status of redundant propulsion system branches and to close-off failed branches;
- the procedures to start, operate and shut-off the propulsion system in orbit or trajectory;
- the off-design use and the off-design procedures in case of propulsion system anomalies.

EXAMPLE The use of AOCS thrusters for orbit raising in case of failure of the apogee boost motor.

(n) Disposal

(1) The UM shall describe how the user of the system can safely dispose of, or neutralize spent propulsion systems.

(2) The UM shall specifically describe the following aspects:

- avoidance of damage of the stage, spacecraft or payload;
- avoidance of creation of debris;
- special operation of the propulsion system for orbit raising or de-orbiting

(o) Limits and constraints

The UM shall list an overview of constraints and limits for the propulsion subsystem or system that under no condition shall be transgressed, including, e.g. the following aspects:

* lifetime;
* maximum number of operation or activation cycles;
* operating temperature range;
* maximum operating power;
* maximum number of cycles in pulse mode operation;
* constraints on duty cycles;
* operational rotating speed range;
* maximum allowed contamination;
* constraints on environmental conditions;
* maximum number of thermal cycles;
* constraints on shock and vibration levels;
* range of mixture ratios.

## <6> Summary and conclusions

The UM shall contain the following:

(a) recommendations for the correct use of the UM;

(b) limitations of the UM;

(c) a statement requesting the user to provide feedback to the propulsion system supplier for statistical evaluation and further improvement of the propulsion system.

# Annex K (normative)

# Mathematical modelling for propulsion analysis (MM-PA) DRD

## K.1 DRD identification

### K.1.1 Requirement identification and source document

ECSS-E-30 Part 5B, subclauses 4.3.2.1.b., 4.6.2.j., 5.6.3.3.b.3., 6.6.7.3.3.h., 6.6.8.4.6.b., 7.6.2.2.a.1.2. and 7.6.2.3.1.b.,

### K.1.2 Purpose and objective

The objective of the mathematical modelling report for propulsion analysis (MM-PA) of propulsion components, subsystems or systems is to describe the mathematical models used for the analysis of a propulsion system, subsystem or component.

The MM-PA is prepared based on the applicable specifications and requirements documentation.

## K.2 Expected response

### K.2.1 Response identification

The requirements for document identification contained in ECSS-M-50 shall be applied to the MM-PA.

### K.2.2 Scope and content

The MM-PA shall provide the information presented in the following sections:

<1> **Introduction**

The MM-PA shall contain a description of the:

(a) purpose, objective, content and the reason prompting its preparation;

(b) propulsion component, subsystem or system for which the mathematical modelling applies;

(c) mathematical modelling for propulsion analysis.

## <2> Applicable and reference documents

The MM-PA shall list the applicable and reference documents in support to the generation of the document.

## <3> Terms, definitions, abbreviated terms and symbols

(a) The MM-PA shall use the terms, definitions, abbreviated terms and symbols used in ECSS-E-30 Part 5.

(b) The MM-PA shall include any additional term, definition, abbreviated term or symbol used.

## <4> General description of mathematical modelling

(a) Overview

(1) The MM-PA shall describe the mathematical modelling and introduce its terminology.

(2) Reference shall be made to the applicable design definition file, inclusive its revision status and the specific mathematical modelling requirements.

(3) If the MM-PA is split into several volumes, each volume shall clearly cross-reference the other volumes, including their revision status and relation to the applicable design definition file.

(b) Coordinate systems

The MM-PA shall describe the coordinate systems used in the propulsion system, subsystem or component for which a mathematical analysis model is made.

## <5> Summary and understanding of mathematical modelling for propulsion system analysis

(a) The MM-PA shall describe the component, subsystem or system that is being modelled, summarize how it is modelled and summarize the objective of the modelling (e.g. performance, thermal, fluid dynamic, or electromagnetic fields).

(b) The MM-PA shall list and summarize the parameters that are used in the mathematical modelling

(c) The MM-PA shall include a discussion on the understanding and clarification of the requirements.

## <6> Description of the mathematical modelling for propulsion analysis

(a) Assumptions, simplifications and models

The MM-PA shall cover

(1) the description of the used assumptions,

(2) the description of simplifications, and

(3) a brief summary of rationale, the modelling method (e.g. analytical, numerical) and software used for the mathematical modelling for propulsion analysis and the related uncertainties.

NOTE Uncertainties can be due to numerical inaccuracies, measurement inaccuracies, models that are based on simplifications and the conditions under which data have been obtained.

(b) Modelling approach

(1) The MM-PA shall include a description and a discussion of the modelling methodology; describing what is done and why, including:

- theoretical modelling, either analytical, numerical or mixed,
- empirical modelling, based on available relevant data,
- evaluation of test results, and
- a combination of the above.

(2) The MM-PA shall state the number of significant digits for all relevant parameters in the mathematical modelling.

(3) The MM-PA shall describe the conditions under which the results of numerical calculations are independent of discretization, i.e. the significant digits as defined in (2) above do not change with further discretization.

(4) The MM-PA shall describe the models.

(5) An estimate of the accuracy with respect to the modelling parameters shall be included in the MM-PA.

(6) The MM-PA shall include a justification and validation of the methodology.

(c) Verification and validation

(1) The MM-PA shall include the demonstration that the applied mathematical models have been:

- validated by independent well-known reference cases;

NOTE Reference cases can encompass independent or published test results, other validated calculation results, comparison with the results of other validated models, or specific tests designed to validate and verify the mathematical model.

- used within their range of validation.

(2) The MM-PA shall include the references by which the mathematical models can be or have been verified.

(3) The MM-PA shall list the range and conditions for which the mathematical models are valid.

(4) In case models have been used without having been validated, the MM-PA shall include a justification why non-validated models have been used.

EXAMPLE Measurements of extremely small forces may be so inaccurate that it is very difficult to properly validate mathematical models by comparison with reliable and sufficiently accurate measurements.

(5) The MM-PA shall include a comparison of the parameters that are used for validation and verification with the corresponding requirements, taking into account the inaccuracies of the parameters.

(6) In case previous models are available, the MM-PA shall include a comparison of the result of the present mathematical modelling for propulsion analysis with the previous ones, and a report on the differences.

## <7> Recommendations

The MM-PA shall include a list with the following recommendations:

(a) Suggestions for future work and additional investigations or improvements.

NOTE In mathematical modelling a continuous efforts is usually done to further improve and refine the models.

(b) Feedback to improve the mathematical modelling.

## <8> Summary and conclusions

In the MM-PA a summary of the results shall be given also describing the limitations of the performed work.

# Annex L (normative)

# Addendum: Specific propulsion aspects for material and mechanical part allowables (MMPal) DRD

## L.1 DRD identification

### L.1.1 Requirement identification and source document

ECSS-E-30 Part 5B, subclause 8.7.3.5.f..

### L.1.2 Purpose and objective

For the purpose and objectives of the material and mechanical parts allowables (MMPal) see ECSS-E-30 Part 2.

This addendum specifies the additional information to be included in the MMPal to cover the specific aspects of a propulsion system, subsystem or component.

## L.2 Expected response

### L.2.1 Response Identification

N/A

### L.2.2 Scope and content

In a MMPal of a propulsion system, subsystem or component, additionally to the information specified in ECSS-E-30 Part 2B Annex L (to be published), the following information shall be given:

<1> **Material properties**

The MMPal shall include a report for the used materials, in case of electric propulsion systems, the sputtering yield due to impingement of ions at energy levels that are representative for the operational conditions of the electric propulsion unit.

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# Annex M (normative)

# Addendum: Additional propulsion aspects for mathematical model requirements (MMR) DRD

## M.1 DRD identification

### M.1.1 Requirement identification and source document

ECSS-E-30 Part 5B, subclauses 5.6.5.1.4.d., 5.6.5.2.2.a.1.2., 5.6.5.2.4.i., 5.6.5.3.2.d., 5.6.5.3.3.c. and 5.6.5.3.12.j.

### M.1.2 Purpose and objective

For the objective of the mathematical model requirement (MMR) see ECSS-E-30 Part 2.

This addendum specifies the additional information to be included in the MMR to cover the thermal aspects of a propulsion system, subsystem or component.

## M.2 Expected response

### M.2.1 Response identification

N/A

### M.2.2 Scope and content

In a MMR of a propulsion system, subsystem or component, additionally to the information specified in ECSS-E-30 Part 2B Annex M (to be published), the following information shall be given:

<1> **Visco-elastic and visco-plastic materials**

The MMR shall include the demonstration that for calculations on materials including visco-elastic, visco-plastic possibly in combination with other structural materials (e.g. the propellant grain in its insulated case, flexseal, skirt connection with rubber, polar boss connections with the composite case), finite element model codes have been used that give reliable results for clearly identified domain of use associated with the processes and conditions for which the material parameters have been characterized.

NOTE 1 Many visco-elastic and visco-plastic materials have a Poisson ratio that equals ½.

NOTE 2 This is especially important for propellant grains.

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# Annex N (normative)

# Addendum: Additional propulsion aspects for mathematical model description and delivery (MMDD) DRD

## N.1 DRD identification

### N.1.1 Requirement identification and source document

ECSS-E-30 Part 5B, subclauses 5.6.5.2.4.k. and 5.6.5.3.12.l.

### N.1.2 Purpose and objective

For the objective of the mathematical model description and delivery (MMDD) see ECSS-E-30 Part 2.

This addendum specifies the additional information to be included in the MMDD to cover the specific aspects of a propulsion system, subsystem or component.

## N.2 Expected response

### N.2.1 Response identification

N/A

### N.2.2 Scope and content

In a MMDD of a propulsion system, subsystem or component, additionally to the information specified in ECSS-E-30 Part 2B Annex N (to be published), the following information shall be given:

<1> **Analysis code compatibility**

The MMDD shall include the demonstration that the selected analysis code, which the model is designed for, gives reliable results for calculations on visco-elastic and visco-plastic materials (e.g. the propellant grain in its insulated case, flexseal, skirt connection with rubber, polar boss connections with the composite case).

NOTE 1 Many visco-elastic and visco-plastic materials have a Poisson ratio that equals ½.

NOTE 2 This is especially important for propellant grains.

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# Index (to be completed by Secretariat!!!)

## A



## B

# C

## D



## E



## F

## G



## H



## I

## J



## K



## L



## M

## N



## O

# P

## Q



## R



## S

# T

## U



## V



## W

# 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-10 Part 1 | Space engineering — System engineering — Part 1: Requirements and process |
| ECSS-E-10 Part 4[1)] | Space engineering — System engineering: Part 4: Interface control |
| ECSS-E-10 Part 17[1)] | Space engineering — System engineering: DRDs |
| ECSS-E-10-02 | Space engineering — Verification |
| ECSS-E-10-03 | Space engineering — Testing |
| ECSS-E-20 | Space engineering — Electrical and electronics |
| ECSS-E-30 Part 1 | Space engineering — Mechanical: Thermal control |
| ECSS-E-30 Part 2 | Space engineering — Mechanical: Structural |
| ECSS-E-30 Part 3 | Space engineering — Mechanical — Mechanisms |
| ECSS-E-30 Part 7 | Space engineering — Mechanical — Mechanical parts |
| ECSS-E-30 Part 8 | Space engineering — Mechanical — Materials |
| ECSS-E-30-02[1)] | Space engineering — Structural design and verification of pressurized hardware |
| ECSS-E-30-05[1)] | Space engineering — Adhesive bonding handbook |
| ECSS-E-40 | Space engineering — Software |
| ECSS-E-50 | Space engineering — Communications |
| ECSS-E-60 | Space engineering — Control engineering |
| ECSS-E-70 | Space engineering — Ground systems and operations |
| ECSS-M-00-02 | Space project management — Tailoring of space standards |
| ECSS-M-00-03 | Space project management — Risk management |
| ECSS-M-30 | Space project management — Project phasing and planning |
| ECSS-M-30-01 | Space project management — Organization and conduct of reviews |
| ECSS-Q-00 | Space product assurance — Policy and principles |


1) To be published.

ECSS-Q-20 Space product assurance — Quality assurance

ECSS-Q-30 Space product assurance — Dependability

ECSS-Q-30-02 Space product assurance — Failure modes, effects and criticality analysis (FMECA)

ECSS-Q-40 Space product assurance — Safety

ECSS-Q-70 Space product assurance — Materials, mechanical parts and processes

ECSS-Q-70-36 Space product assurance — Selection of materials to control stress-corrosion cracking

BSR/AIAA S-080-1998 Space systems — Metallic pressure vessels, pressurized structures and pressure components

BSR/AIAA S-081-1999 Composite-overwrapped pressure vessels (COPVs) for space and launch vehicles

CPTR 96-64 Electrical propulsion for space applications CPIA, Dec. 1996

CPTR 97-65 Electric thruster systems, CPIA, June 1997

EN 13701:2001 Space systems — Glossary of terms

ISO 14304 Space systems — Criteria for explosive systems and devices used on space vehicles

ISO 14644-1:1999 Cleanrooms and associated controlled environments. Classification of air cleanliness.

ISO 14952 Space systems — Surface cleanliness of fluid systems

ISO 14623 Space systems — Pressure vessels and pressurized structures design and operation

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

ISO 15389: 2001 Space systems — Flight to ground umbilicals

JPL 82-62 Propellant/material compatibility program and results

MIL-STD-1774 Process for cleaning hydrazine systems and components

MIL-STD-1541 (USAF) Electromagnetic compatibility requirements for space systems

MIL-STD-461 Requirements for the control of electromagnetic interference emissions and susceptibility

MIL-STD-1576 Issue 31/7/84 Electro-explosive sub-system safety requirements

MIL-STD-1246 C Product cleanliness levels and contamination control program

NAS 1638 Cleanliness requirements of parts used in hydraulic systems

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

NASA-MSFC-SPEC-522B Design criteria for controlling stress corrosion cracking

ST/SG/AC/10/1.Rev. 7 UNO Transport of dangerous goods

ESA-PSS-03-210, Issue 2 Adhesive bonding handbook for advanced structural materials

**Draft ECSS-E-30 Part 5B**
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EUROPEAN COOPERATION
ECSS
FOR SPACE STANDARDIZATION

# Space engineering

## Mechanical - Part 5: Propulsion

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# A



# B

## C

# D

# E

# F

# G



# H

## I

## J



## K



## L

# M

# N



# O

# P

# Q



# R

## S

# T

## U



## V

## W