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Safety Assessment of Solid Propellants for Satellites Engines

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In the aerospace industry, the development and production of propellants to be used for the launching of missiles carrying satellites is an issue gaining more and more importance, along with data transmission and all other activities requiring the use of satellite systems. Research is mostly involved in the setup of new products in terms of both propellants (solid and/or liquid) and engines, having better characteristics in terms of weight, size, manoeuvrability and control.
This represents a challenge for the chemical industry both for the research and development of new products and for all the safety aspects related with the main production process and all the “side activities” connected with it (handling, transportation, assembly, etc.) and, finally, with the launching of the carrier of the so-called *pay-load*, i.e. the satellites to be put into orbit.
Risk analysts are thus required to provide effective, reliable and timely results in terms of risk assessment and accident scenarios identification to enable the definition and implementation of the most proper prevention and protection measures for all the production phases.
In the present paper, based on specific past experience, some of the critical elements which can be encountered in the risk analysis of the production process of aerospace propellants/engines, will be addressed.

1. General and specific aspects of accident scenarios assessment

Similarly with all other areas of application, risk analysis involves first of all the identification and assessment of all the accident scenarios connected with the activities of R&D, production, transportation, assembly and launching of the carrier, by carefully taking into consideration all the technical and procedural aspects of these activities. Of course, this has to be accomplished in compliance with all the regulations addressing both health and safety issues for the workers inside the plant and the surrounding people possibly exposed to the risk, and those addressing the environmental issues.
The whole risk analysis procedure involves different steps and requires specific and detailed competences, experience and knowledge of all the production phases.
Here, specific attention has been devoted to two aspects of the analytical process:

1. The identification of the sources of ignition, i.e. the direct or indirect causes that can trigger the propellant combustion;
2. The evolution of the accident scenarios after the accidental ignition of the propellant.

Finally, some short critical remarks on the calculation methods for the physical consequences of the accident scenarios will be given.

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1.1 Identification of the ignition sources

Given the probabilistic approach adopted by the risk analysis procedure, *all* the possible causes that can give rise to an accident should be identified, and in particular the ignition sources that can accidentally start the combustion of the propellant. This will require a thorough and detailed knowledge of all the phases of the production process.

In general, the following aspects have to be taken into consideration:

- **External events**, i.e. events and/or conditions that might happen outside the production plant where the propellant or other intermediates are produced or stored; these might be natural events (atmospheric conditions, earthquakes, etc.), events caused by other human activities, or caused by accidents in a nearby production unit or even neighbouring industrial installations (domino effect);
- **Internal events**, i.e. accidents and/or dangerous conditions developing within the same production area where the propellant (or intermediate) under consideration is handled;
- **Functional events**, i.e. faults, malfunctioning, or failures involving the production equipment.

The most important information required for accomplishing a reliable and meaningful analysis involves:

- A detailed knowledge of the production site and of the surrounding environment;
- A detailed knowledge of the production process and of the layout, also referred to all the utilities (power production, steam, storage, and so on), transportation pathways and modalities, etc.;
- A detailed knowledge of the chemical characteristics and reactivity of the solid propellant and of all the reactants and intermediates.

With specific reference to the latter issue, it is of the utmost importance the availability of technical and scientific data, possibly derived from experimental tests on a lab scale or pilot plants, regarding the reactivity (both stoichiometry and kinetics) of the propellant and its intermediates under the critical conditions previously identified.

With the exception of the basic components of the propellant, whose characteristics and peculiarities are usually already known, in all other cases (propellant and intermediates) this information has to be specifically obtained case by case.

The classical and widely used techniques of HazOp (*Hazard and Operability*) Analysis and FMEA (*Failure Modes and Effects Analysis*) can be of great help during this phase. They allow identifying the so-called Top Events, i.e. the accidental events and their possible causes, based on:

- External conditions enabling the transfer of energy to the flammable mass able to ignite it;
- Process conditions where the possibility of large input of thermal or mechanical energy is present;
- Availability of very large flammable inventories, even just in storage and in the absence of process operations.

1.2 Potential evolution after propellant ignition

A detailed knowledge of the possible evolution of the accident following the initial ignition is very important since it will directly affect all the prevention, protection and mitigation measures to be implemented by the plant management for the safety and health of the internal personnel and the surrounding environment, also in accordance with the regulation in force (NASA 1962; NASA 1993; U.S. Department of Energy, 1994).

Propellant are usually classified by the UN/ADR rule as a class 1.3 substance. However this generic classification allows a wide variability for the actual behaviour of the chemical after ignition and thus for the actual possible final consequences; furthermore, this approach does not take into account the actual storage and handling conditions of the material, which nonetheless play a fundamental role in the risk assessment.

In the case of solid propellant engines, with particular reference to their final configuration, some general considerations can be drawn regarding their potential evolution, and the following possible scenarios can be identified:

- Detonation of one of the component segments with the generation of a blast wave and launching of projectiles
- Physical explosion (blast wave) of a segment vessel following a sudden pressure increase, with launching of fragments and possible additional thermal effects;

- Uncontrolled self-propulsion of the segment;
- Slower combustion of the propellant with thermal effects.

The above scenarios are analyzed below with more details.

Detonation

It is by far the most complex phenomenon to be analyzed, due to the many parameters and boundary conditions affecting the reactivity of the chemical and thus the actual occurrence of this very dangerous event.

The two main parameters associated with the likelihood of occurrence of the detonation of a solid propellant are:

SDT (*Shock to Detonation Transition*) – It represents the transition to detonation generated by strong mechanical loads (blast waves with overpressure of some tenths of kbar, and velocities above around 900 m / s);

DDT (*Deflagration to Detonation Transition)* - especially important for porous materials. It is directly linked with the mechanical characteristics and the reactivity of the material and with the boundary conditions during storage and/or handling.

For a solid propellant, the assessment of the SDT phenomenon is dependent on the following parameters:

- The *critical diameter* (D_c): it represents the inherent minimum diameter needed for the material to be triggered by a shock wave;
- The *shock sensitivity (IAD – Detonation attitude index):* it is assessed by means of a standard test (STANAG 4488) consisting in the determination of the minimum number of cellulose acetate cards to be packed together in order to avoid the transmission of the detonative effect from a 320 g charge to the test material. The higher the number of cards, the higher the likelihood of detonation of the substance in case of ignition;
- *TNT equivalency*: it represents the mass of TNT (trinitrotoluene) equivalent to the mass if propellant under investigation in terms of effects and overpressure profile.

The parameters to be quantified for the assessment of the DDT are:

- The *critical pressure* (P_c): it represent the shift from a conductive combustion (regular combustion) to a convective one (deflagration);
- The *impact speed limit*: beyond this value, the propellant subjected to a mechanical loading will significantly degrade (brittle) and the combustion will not involve parallel layers but will cause the detonation of the fragmented material.

The quantification of the above parameters will allow the analyst to assess the likelihood of this phenomenon.

A typical solid propellant is usually characterized by the below values:

- Compact and non-porous structure;
- Shock sensitivity (IAD): less than 1 card;
- Impact speed limit**:** higher than 150 m/s (201 m/s);
- Critical pressure: higher than 15 kbar (1500 MPa)
- Combustion rate at atmospheric pressure: about 1.1 mm/s.

Physical explosion

The physical explosion of a segment is usually represented by the mechanical failure of the vessel containing the propellant because of the overpressure associated with the propellant combustion after ignition.

This event can also be triggered by a thermal or mechanical impact on the propellant due to an external fire or to a strong mechanical impact on the containment structure. Once ignited, the propellant can burn possibly leading to the failure of the containment system and the launching of fragments of the container and the propellant itself.

However, it must be noted that since solid propellants usually have relatively low combustion rates, and they usually burn by parallel layers, in many cases the launching of fragments is limited. Furthermore, the adoption of proper safety systems allows to keep the pressure in the containment vessel within a few bars.

Self-propulsion
In case of ignition of the propellant through the central channel, self-propulsion can occur when the boost of the combustion gases is larger than the weight of the propellant in its storage or manoeuvring configuration.
However, in an attempt to avoid this possibility, the solid propellant stages are usually arranged in a proper configuration; in case of an accidental ignition (non piloted) combustion gases are generated on both sides of the segment; finally, the sum of the mass weight of the propellant and of the supporting devices in a stage is usually much higher than the boost provided by the combustion gases.

Combustion
Based on the characteristics of solid propellant engines in their final configuration, the most likely event is represented by a fire. In fact, in case of ignition the propellant will burn with the generation of radiation effects and combustion products. The propellant combustion will give rise to different consequences depending on the combustion modalities and on the level of confinement within the engine. Under controlled conditions (usually obtained during normal operation), the combustion of the fuel will produce a high temperature (some thousands degrees) directional jet-fire characterized by a considerable length (for large engines up to some tenths meter), required for the necessary boost (Martinsen and Marx, 1999).
When the combustion involves the propellant outside the engine, but still in a confined environment (such as the storage area), it can spread to the whole mass of material with a large and rapid release of energy possibly giving rise to sensible overpressures in the surroundings. This can finally end in heavy structural damages and launching of objects.

1.3 Consequences modeling
Once all the final accidental scenarios have been identified, their consequences have to be modeled and the corresponding impact areas calculated.
During this step, the regulations in force in the Country of interest have to be properly taken into consideration. Apart from particular issues dependent on the specific Country, they commonly identify “critical areas”, surrounding the production plant, to be regulated from a land use planning point of view, and to allow/limit access and/or use.
In general, the consequences taken into consideration by the different National regulations, refer to the possible damages to people and the environment in the proximity of the production site, and in particular:

- Overpressure (produced by explosions);
- Thermal radiation (transient or steady) from a fire ;
- Launching of projectiles (following the failure of a container or the explosion of the solid fuel itself).

Of course, in the case of the accidental combustion of the solid fuel, all the above consequences are simultaneously found.

In the assessment of the overpressure, the traditional method of the TNT equivalency is commonly applied, where a commonly used equation for the calculation of the overpressure is given by Brasie and Simpson (1968) and Baker et al. (1996).

$$P = 67\left(\frac{1}{Z}\right) + 370\left(\frac{1}{Z}\right)^2 \tag{1}$$

with

$$Z = \frac{M^{1/3}}{R} \tag{2}$$

Z being the normalized distance ($kg^{1/3}/m$) corresponding to the actual distance from the explosion centre R (m), P the peak overpressure (kPa) and M the equivalent mass of TNT (kg).
As usual, this method is characterized by a large uncertainty on the equivalent mass of TNT: values ranging from as low as 0.1 %, up to about 110 % are often found in the literature, reflecting the many possibilities among deflagrations and detonations. This is a significant uncertainty for the risk analyst. It is worth reminding that the commonly reported values of the TNT equivalent mass are usually obtained from so-called boostered tests, and these values are often quite higher than those associated with more ordinary accidental conditions (such as sparks, friction, and so on).
In the case of an internal explosion occurring inside the propellant vessel, and possibly leading to the failure of the metal shell, the calculation follows an approach similar to that used for representing BLEVE explosions, and the deflagration energy is calculated as per Baker et al. (1975):

$$E = p_a V\left[\left(\frac{p_1}{p_a}\right)^{1/\gamma}\left(\frac{\gamma}{1-\gamma}\right)+1-\left(\frac{1}{1-\gamma}\right)\left(\frac{p_1}{p_a}\right)\right] \qquad (3)$$

where p_a is the ambient pressure (Pa), p_1 the initial pressure within the engine (Pa), γ the isentropic coefficient of the gas and V the initial gas volume (m^3).
As far as the thermal effects are taken into account, based on both experimental results and theoretical models available in the literature, the combustion of the solid fuel, even after an accidental ignition, occurs mainly as a relatively slow combustion, progressively involving parallel layers. This is the most likely scenario among the fire ones, and will give rise to a strongly directional flame (depending on the segment configuration) and to the release of high temperature combustion gases.
Usually two fire types are assumed: a “steady” one, representing the “nominal” combustion with constant radiation in specific directions and which is modelled like a jetfire, determining the geometrical configuration and emitted radiation; and a “transient” one, like a fireball, where the duration of the fire is proportional to the total flammable mass available.

In the latter case the parameters required for the calculation of the fireball can be obtained from the literature, or derived from specific studies on solid propellants, like the one reported by the Centre Nationale d’Etudes Spatiales (CNES, 2000):

$r = 1.21\ M^{0,366}$ (4)

$t^* = 3.225\ M^{0,320}$ for M<800 kg (5)

$t^* = 0,707\ M^{0,405}$ for M>800 kg (6)

where M is the total flammable mass (kg), r the fireball radius (m) and t* the fireball duration (s).
The emissive power from the fire surface is calculated based on the total combustion energy:

$$E = \eta\left[\frac{E_{tot}}{2\pi t r^2}\right] \qquad (7)$$

where η is the radiation fraction of the total emitted energy E_{tot}, given by the product of the total mass M by the combustion energy C (J/kg).
The values obtained by the two methods have finally to be compared with the threshold values provided by the National regulation in force.

2. Conclusions

An adequate and accurate application of the risk analysis methodologies to a peculiar area such as the production of aerospace systems (both fuels and engines) is hampered by the unavailability of proper and commonly recognised standards of both the National regulations and of the technical rules. Different often conflicting references and data are available in the literature, sometimes even in contrast with the regulation in force. A strong need for standardization and for agreement on the most proper methods is present. Despite it represents a very peculiar industrial sector, the risk posed by the production plants of aerospace systems (fuels/engines) on the surrounding area is nonetheless not negligible, and an effort in this direction by both risk analysts and process technicians is strongly urged.

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