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SOME CONSIDERATIONS IN SUPPORT OF SOLID PROPULSION FOR SPACE DEBRIS DISPOSAL

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Abstract. *Some considerations on the use of solid rocket motors for space debris disposal are presented. From the synthesis of a de-orbit sample mission and a trade-off study on costs and benefits, a solid propellant unit for end-of-life missions and debris in-space disposal missions is evaluated. The enhanced operation flexibility, the propellant development and an advanced ignition concept granting multiple and independent firing capability of a new solid propulsion concept are discussed.*

1 INTRODUCTION

Nowadays, space debris has become an urgent problem that needs prompt answers from the global worldwide community. Uncontrolled orbiting objects, no matter if they are de-activated satellites, exhausted rocket stages or chunks of space systems, represent a threat for space missions in general and should be removed from the sky [1].

Recently, some uncontrolled space debris represented a serious threat for human and commercial space activity and demonstrates that urgent measures of mitigation and limitation must be promptly enacted by the actors of space exploitation.

A recent major risk involved the mission of Atlantis Space Shuttle while docking at the ISS (International Space Station) on May 15th, 2010.

Different efficient techniques were and are discussed for the implementation of space-debris de-orbiting systems but any action has not yet been put in practice. Chemical propulsion seems to have the technology readiness and the affordability requested by this kind of mission but performance is quite low [2-4].

A trade-off study on costs and benefits about de-orbiting system demonstrated that the most convenient technology is solid propulsion but this is true only when mission is well defined and specifications are known in advance [5].

Limited flexibility may represent a major solid propulsion drawback and actually limits the application to very few missions where absence of throttling is not a major concern and high energy density represents a major benefit. For this reason it is possible to find solid propellant for in-space manoeuvres of orbit insertion.

Several other methods are applicable to the de-orbiting maneuver but current readiness of their technology is not adequate to the needs of the most urgent actions. Moreover, if mitigation strategies are not developed in compliance with cost-containment, the debris mitigation may become unbearable.

In this sense, it is necessary to imagine that a mission of debris removal can be accomplished for a large part of the disposable orbiting space objects with the same propulsion unit. Evaluation studies report that solid propulsion represents today the most convenient way to accomplish the project.

In this paper we discuss the development of such new category of solid propulsion systems.

2 IN-SPACE RE-IGNITABLE MOTORS AND UNCONTROLLED DE-ORBITING

The utilization of the same solid propulsion unit for a mission of multiple debris removal intended for a large part of the disposable orbiting space objects introduces many requirements to the rocket motor. One of the most relevant is the in-space re-ignitability motor capability.

Several attempts were done in the past to add this appealing feature only to small solid propulsion systems since current large rocket boosters are not interested in this development due to their single-shot operation [6-9].

Multiple firings are usually attained by using separated cartridges of propellants with independent ignition systems. Sometimes propellant is stored in different combustion chambers that discharge in one single nozzle while more compact design considers multiple propellant casts in the same liner, separated each other by a proper inhibition method. In any cases, the firing time is predetermined and the addition of a commanded extinction seems quite complicated if the system has to be reignited afterwards.

In a sense, the use of multiple cartridges with short firing duration allows at least the possibility to have a discrete regulation on total firing time and, thus on total impulse.

Even with increased multi-firing flexibility, a class of convenient de-orbiting missions and relevant altitude ranges should be well targeted. Initially, it is possible to focus on so-called “uncontrolled” de-orbiting missions, for matter of simplicity. These operations can be performed by moving an orbiting object to an altitude where it is sensitive to the action of atmospheric drag. Orbit altitude is progressively reduced and the decay time can be roughly estimated [7].

Choosing one range of orbiting debris and altitude from the compliance criteria according to ESA's debris mitigation guidelines [10], velocity requirements for the mission can be easily evaluated once the initial and the final orbits are identified. For this scope, an extended data collection should be needed and, effectively, a constant monitoring of orbit population is now performed by the space community that supplies useful instruments and databases like DISCOS which is a collection of information maintained by ESA [11]. In this list it is possible to find any kind of space debris, such as exhausted upper stages of launchers, de-activated satellites, as well as chunks of systems originated by collisions or explosions.

3 COMPOSITE PROPELLANT AND END-OF-LIFE ROCKET MOTORS

In the frame of all space activities, solid propellants were developed or adapted for numerous applications involving launchers stages, pyrotechnics, auxiliary propulsion, satellites, and spacecrafts. Considering a propulsion unit specific for space application, Class

1.3 energetic materials are usually considered for safety and handling reasons. Rather, explosive materials belonging to Class 1.1, are unacceptable even though they might be used in a specifically designed systems and military environments. In the former category, composite propellants represent the footing of all modern developments of solid rocket propulsion systems. These are heterogeneous mixtures of oxidizer and fuel powders bound together by a polymeric binder. Fluorine derivatives, perchlorates, nitrates, and nitro compounds represent some examples of oxidizers. Polymer binder and, in most cases, metal powders represent the fuels to burn. Propellants can contain also additives, generally at low contents, used as stabilizers, afterburning suppressants, combustion instabilities suppressants, and burning-rate modifiers.

Thanks to an intense development of propellant binders in the 70s, hydroxyl terminated polybutadiene (HTPB) is now considered one of the best options and, out of this family, R-45 pre-polymer resulted in higher solid loadings and better rheology even with ultrafine AP, which means higher specific impulse and density, and extended operating temperature range [12-14].

If no metal fuel is added to a standard AP/HTPB composition, reduced smoke propellants are obtained because the exhaust plume is virtually exempt from condensed combustion products (CCPs). This feature makes this class of propellants very attractive for end-of-life motors. Nevertheless, even with high loading fraction the sole use of non-energetic binder and AP delivers to a relatively low specific impulse. Some metals, and more specifically aluminium, supply higher performance but their combustion generates condensed combustion products that are discharged from the nozzle. Recently, other advanced additives such as hydrides and boron-based compounds are addressed by research activities [15-17]. Thermochemical investigations (based on Gibbs free energy minimization [18]) revealed joint ability to deliver higher specific impulse with reduced amount of condensed combustion products. Moreover, high speed and resolution visualizations of the combustion surface demonstrate that such condensed products do not agglomerate.

Even though these propellants are not CCPs-free, they may represent a good compromise between debris mitigation requirements and performance and should carefully be evaluated. Anyway, these innovative propellants have to demonstrate their affordability in a production system.

The use of innovative fuels poses also the question of the combustion models to be used as a support to the development of both propellant and rocket. Since the '60s combustion principles of catalyst-free AP composite propellants were investigated by flame models and condensed-phase models. For the former part, specific theoretical frameworks were developed for composite propellants such as Summerfield's GDF (granular-diffusion-flame) model or, later, Beckstead's multiple flame BDP model based on a complex interaction between the oxidizer and binder phase. Some extensions to doped propellants were also attempted [19-22]. Other homogeneous approaches tried to identify the profile of heat release in the gas-phase (KTSS, Alpha-Beta-Gamma models) and were coupled with a condensed phase model [23]. Modern developments by Jackson's Rocfire code lead to full 3D interaction between heterogeneous condensed phase and reactive flowfield, even with recent attempts to simulate also aluminium hydride and nanoaluminum combustion [24-26]. The interesting point here is given by the presence fuels with high reactivity or gases with high diffusion such as hydrogen or boron. The results of modeling and validation attempts suggested that development and tuning of propellants under specific rocket conditions still requests a series of fire tests and specific data reduction techniques, such as thicknessover-time methods or more advanced fitting procedures [27].

3 A ROCKET UNIT FOR END-OF-LIFE AND IN-SPACE DISPOSAL MISSIONS

A new project concept can target the development of a rocket array with multiple firing capabilities, specifically designed to de-orbit debris already present in the space. The system is supposed to start its mission after its docking onto a debris, assuming that a robotic mission would do this job in a mood similar to the Automated Transfer Vehicles (ATV), recently tested by ESA.

Thanks to the compact design of the array granted by multiple small propulsion units, after a specific re-design this unit may be part of the initial equipment of future space systems.

The concepts discussed here disregard the docking mission.

An initial activity must focus the definition of a class of missions that can conveniently be operated with a solid rocket unit. Data collection about space debris will be carried out by using public DICSCOS database released by ESA looking for a sample mission for object disposal through uncontrolled re-entry. This activity will state the range of mass and of initial altitude that will be addressed by this project. Velocity evaluations will be supplied on the basis of simple orbital computations in compliance with ESA debris mitigation guidelines (orbiting time < 25 years). System specifications will be discussed and the rocket specifications, as of thrust profile, firing time, and combustion pressure will be frozen.

Once that thrust profile and combustion pressure are fixed, can start the development of a solid propellant that suits for mission accomplishment. An initial wide investigation will be completed through literature review then followed by extended thermochemical computations. General guidelines of this development will look after high specific impulse, low condensed combustion products, and availability of raw material. Thermochemical tests will pass some compositions to a first level of experimental evaluation performed on limited batches of propellants and mainly focused on density and porosity characterization and combustion behavior.

Porosity evaluation can come from the comparison between theoretical and experimental density and can be used to assess the quality of both lab scale and, later in the project, of scaled-up formulations.

The combustion tests can be performed in a stainless steel vessel, capable to stand pressure values up to 110 bar and with suitable total volume. The vessel must be equipped with some windows for a complete visibility of the combustion which takes place in an inert atmosphere of nitrogen. An automated exhaust system made by an array of servo-controlled valves, a pressure transducer and a controller keeps the pressure within a given range also during the combustion. Ignition is demanded to a standard hot wire technique. Burning rate measurements can be demanded to a specific optical technique that uses a high speed and high resolution video camera and software specifically designed for combustion tracking. The same apparatus, equipped with a long-range microscope and a cold-light source can also be used to study the combustion dynamics on the burning surface. Thanks to this technique, the generation of CCPs can be recorded and monitored. All this set of tests will represent the first criteria of selection and supply an initial dataset for the initial development of the rocket.

An extended characterization will be then performed on a short-listed selection of formulations looking at the characterization of other combustion properties, mechanical features and propellant survivability to space environment. Among the combustion properties addressed in this phase, PDL (pressure deflagration limit) is of primary concern for space applications being the minimum pressure for a self-sustained combustion. The PDL tests can be conducted in a 40 litres vessel where pressure is progressively reduced by a vacuum pump. Vessel size is chosen in order to damp pressure oscillations that are typical of near-PDL zones. Samples will be parallelepipeds of different shape factor, and sizes.

Flame extinction can be traced by the signal of a photodiode, along with the recording of pressure. The propellant strands must be long enough to permit depressurization with a typical gradient of 1-0.2 mbar/s, in order to avoid any possible dynamic effect due to fast depressurization. Ignition delay can be evaluated in a normal atmospheric and sub-atmospheric pressure range using CO2 laser radiation impinging on the sample. The ignition latency can be recorded by a photodiode and tests can be conducted in sub-atmospheric range of pressure as well as atmospheric pressure. Temperature profiles in the solid phase can be recorded through micro-thermocouples, assessing thermal diffusivity of the propellant and surface temperature for low pressure. The investigation of mechanical properties can involve a series of uniaxial tensile tests carried on at ambient temperature as well as dynamic mechanical analysis that can optionally be conducted also changing the temperature, coming to the definition of a master curve of the propellant.

Tests on propellant survivability in space can be implemented in a simulated environment thanks to a container where a vacuum pump reduces the inner pressure. The vessel is then placed in a specific oven where thermal cycles are imposed for a limited period of time. In fact, it is presumable that a disposing mission that targets a space debris already in space will have a short duration in the order of few days. Samples cut for mechanical and combustion tests can be characterized after short-term aging and data can be compared to new materials, even for energetic release through calorimetric tests. Given the complexity to implement and execute this kind of aging tests, only few release-candidate formulations must be considered.

Slow-burning propellants may represent one option for this kind of mission. Compositions will be based on cured Hydroxyl Terminated Polubutadyene (HTPB) as fuel-binder and Ammonium Perchlorate (AP) with some possible addition of Ammonium Nitrate (AN) as a minor fraction, to be evaluated during the project. Medium size AP (80-90 μm) will be first considered to avoid combustion anomalies such as flame suppression and combustion instability, widely reported in literature when fine AP burns in HTPB. Preliminary burning tests reported a regression rate of about 0.75-0.8 mm/s at 20 bar. A fine tailoring of the burning rate can be achieved by means of high-tech catalysts, such as different kinds of nanometric Iron Oxides or changing oxidizer powder size, always assessed by means of laser granulometric analysis.

These formulations are expected to feature quite low specific impulse though, and fuel powders should be included in the propellant if a competitive formulation is requested. Given the final scope of the project, extra solid debris should not be generated by propellant combustion leading to the immediate ban of metal fuels and turning to high energy additives such as metal hydrides or advanced boron-based ingredients. Different issues arise with this choice. A comparative investigation has to evaluate if a limited amount of dust-size CCP emission with respect higher performance can be acceptable.

Thanks to this large set of experimental data, intense modeling work can be carried on using realistic datasets. The modeling approach can be based initially on homogeneous 1D solid-phase and flame models to assess steady and unsteady propertied of the propellant under different operating conditions to get ballistic fitting, pressure coupled behavior, ignition, extinction transitory or thermal wave thickness. Only in case of need, more refined approaches may be considered.

Both the analysis of experimental rocket firings and modeling results are requested for the study of the ignition transitory and the relevant systems that will grant multiple firing capability.

The design and the lab-scale demonstration of the multi-ignition concept can follows the guidelines supplied by patents available in the open literature, a multi-grain approach can be addressed, each supplied with an ignition device such as a hot wire. A method to separate firings must be implemented. Initially it is possible to use calibrated disks that separate the charges and allow some pressure rise before disk breakup, easing ignition. Disk breakup may damage the nozzle, though. Moreover, some debris are generated. New concepts must be also explored, always working on the idea of separate the combustion.

5 CONCLUSIONS

From the definition of general de-orbit mission specifications a proper dataset is collected and analyzed, a classification of possible debris-targets with the corresponding relevant specifications are released and a de-orbit / debris-disposal sample mission is defined.

This mission demonstrate that also solid propellant may work fine for end-of-life missions, for a matter of compactness and reliability and their greatest disadvantage - that is the lack of controllability - becomes less important.

An advancement concerns to enhance the flexibility of operation for the solid propulsion unit. This specific activity is carried out in conjunction with propellant development and focused on an advanced ignition concept granting multiple and independent firing capability to each rocket of a complex system.

A new solid propulsion unit made by an array of solid rockets, each capable of multiple independent firings is identified. The development of a new solid propellant formulation specifically designed to equip the propulsion unit is then discussed.

It is likely that for this kind of missions relatively low levels of thrust are required, in the order of 1-10 N depending on mass and resistance to acceleration fields of the target object.

The system can be based on separated propellant cartridges, each equipped with an independent ignition system.

Given the final scope of debris limitation, also propellant development must comply with a low-to-zero emission policy, avoiding contamination of the space due to condensed combustion products (CCPs). Initially, nonmetallized consolidated propellant formulations are proposed. However, in order to increase propellant performance, addition with high energy novel ingredients such as hydrides or boron based powders are considered. Propellant choice come from a trade-off analysis of benefits and problems related to condensed combustion emission, propellant features, and short-term survivability in space.

The prediction of both steady and unsteady operations of the rockets is necessary to assist a rapid development of the project at any level. For this reason, along with the experimental activity, different combustion models must be implemented and fitted to the experimental data that become available.

Modeling quality is refined as long as rocket fire tests are performed and, after a proper data reduction, it is possible to compute the ballistic scale factor between lab-scale and rocket-level combustion.

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