Impact of the Arrival of Micro/Mini-Launchers and Micro-Satellite Constellations on RAMS Activities

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The space transportation is entering an area of expansion and innovation. Micro/mini-launchers projects are multiplying to meet the needs of New Space players to put into orbit large quantities of small satellites. In order to reduce their costs, they are counting on a simplification of operations for high launch rates, and are looking for flexible launch sites. The Europe's spaceport, the Guiana Space Center, will offer many advantages for hosting this launcher's family, while guaranteeing the safety and reliability of flights. The deployment of large constellations of small satellites raises the problem of orbital debris on usual Earth orbits. Currently, only a small percentage of satellites is deliberately deorbited. The resulting risks of collisions and explosions in orbit has led to the implementation of preventive and corrective actions at national and international levels. In this context, the improvement of the satellite reliability model during its life is a key to choose the best moment and guarantee the operations of passivation and deorbitation for satellites at their End-of-Life. To face these new Reliability and Safety problematics, the RAMS departments at the French Space Agency (CNES) are working on new methods to cope with the New Space background.

Keywords: Micro-launcher, Mini-launcher, Micro-satellite, Reliability, RAMS, Space, New Space, Safety.

1. Introduction

The European space transportation is entering an area of expansion, innovation and partnership. Since few years, micro/mini-launchers projects (around 30 meters, some with potential reusable capacities) are currently multiplying in particular to meet the needs of New Space players to put into orbit large quantities of small satellites for constellations. With this, industrials organizations are emerging allowing more flexibility in the development (new technologies, new development methods, more agile). In order to reduce their costs and make their activity profitable, these new entrants are counting on a simplification of operations for high launch rates, and are looking for flexible launch sites adapted to this new concept.

The Europe's spaceport, the Guiana Space Center – CSG, is at the epicentre of this ecosystem of micro/mini-launchers with the ELM (Micro/mini-launchers Launch Complex).

Fig.1. Location of French Guiana

It will offer many advantages for hosting this family of launchers, and by 2026 should allow a high launch rate, while guaranteeing the safety and reliability of ground operations and flights (see article presented at the last Ground Based Space Facilities symposium [4]).

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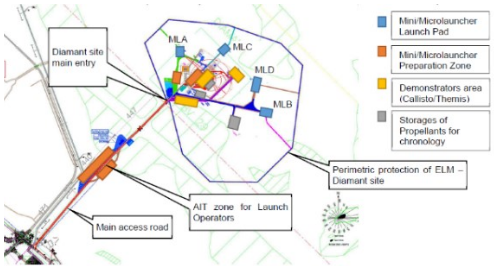

Fig.2. Projected ELM layout

However, new developers mean new risks and the feedbacks of the launchers in the world show that 80% of a new actor's first launch is a failure, proving that designing and developing a launcher is difficult. Furthermore, on the 31 (6%) worldwide launch failures from 2020 to march 2023 (for a total of 499 flights), 23 (75%) came from micro/mini-launchers and 8 (35%) of them were maiden flights.

Table 1. Micro/mini-launchers maiden flights failures between 2020 and March 2023

Date	Launcher	Launch Range	Failure mode
03/23	Terran-1	Florida, US	2nd stage thrust stop
01/23	RS1	Alaska, US	1st stage thrust stop
12/22	Zhuque	China	2nd stage engine failure
10/21	KSLV	South Korea	3rd stage propellant leakage
09/21	Firefly	Florida, US	1st stage failure
08/21	Astra-Rocket	Florida, US	Guidance failure
07/20	Kuaizhou-1A	China	3rd stage failure
05/20	LauncherOne	California, US	1st stage engine stop

The current deployment of constellations of thousands of satellites and the constant increase of the number of space debris has led to the establishment of standards by several international organizations to encourage global effort to deal with this issue. They require, among others:

- To avoid accidental break-ups in Earth orbits during operations and after the end of the mission by passivating all the sources of energy stored on board;
- To remove spacecraft and launch vehicles orbital stages from the Low Earth Orbit (LEO) region through a re-entry within 25 years, and Geosynchronous (GEO) protected regions through manoeuvres to a higher orbit of about 200 km.

In this context, the success of End-of-Life (EoL) operations is a major requirement: it directly determines the long-term evolution of the debris population in flight. The update of the satellite reliability model and the resulting probability of successful EoL operations during the satellite life – with regard to the different anomalies experienced by the satellite – constitutes one of the criteria for initiating an EoL or approving a mission extension.

2. French Law on Space Operations

In order to ensure safety during operations (on ground and during the flight) for launchers operated from the CSG, CNES is responsible for the respect to the French Space Operation Act (FSOA/LOS, [1]) and its associated applications rules, in particular the Technical Regulation (RT, [2]) and the Decree regulating the operation of the Guiana Space Center facilities (REI, [3]).

The FSOA [1] decrees that every operator has to carry out an impact assessment on the environment, and a hazard study with a plan to manage risks and ensure safety of populations, properties, public health and the environment. The authorization process and the assessment of compliance with the RT [2] provides assurance that the operators have the means, resources, necessary skills and are appropriately organized to perform the operation in compliance with the law. An article has been presented on the subject during the 8th conference of the International Association for the Advancement of Space Safety, see [5].

3. Launcher Safety and Reliability

Hazard class categories are defined in the REI [3], according to severity of the damages:

Hazard class	Definition of damage
With **catastrophic** consequences	<u>*For ground-based activities*</u> ▪ Immediate or delayed loss of human life

– known as G0A	▪ Permanent invalidity ▪ Irreversible harm to public health *For in-flight activities* ▪ Immediate or delayed loss of human life ▪ Serious injury ▪ Irreversible harm to public health
With **severe** consequences – known as G0B	*For ground-based activities* ▪ Serious injury to individuals leading neither to loss of human life nor permanent invalidity ▪ Reversible harm to public health ▪ Significant property damage: - Total or partial destruction of public or private property - Total or partial destruction of a facility critical to the launch operation ▪ Significant environmental damage

Qualitative requirements are defined according to the above-mentioned hazard class categories.

- For all hazardous activities with a risk of severe consequences, the space system must comply to the single failure criterion requirement. It means that no single failure must entail a risk of severe consequence (known as "Fail Safe" – FS).
- For all hazardous activities with a risk of catastrophic consequences, the space system must comply to the double failure criterion requirement. It means that no combination of two independents failures must present a risk of catastrophic consequences (known as Fail Safe / Fail Safe – FS/FS or Fail Operational / Fail Safe – FO/FS).

Quantitative requirements are defined only for hazardous activities with a risk of catastrophic consequences:

- For ground-based activities, the maximum allowable probability of causing at least one victim (collective hazard) included in the design of the launch systems, test benches and associated technical resources, is 10^{-6} per launch preparation or test campaign.
- The flight requirements fall within the general framework set by the RT [2]:
  - (i) 2.10^{-5} for the entire launch phase and orbital re-entry
  - (ii) 1.10^{-7} for the nominal fallout of the launcher elements

All micro/mini-launchers who want to launch from the CSG must obey to these regulations. They ensure:

- Safety during operation of the launcher on ground with regard to operators (G0A) and wrt installations and means (G0B);
- Safety during the flight (Safety & Intervention mission) wrt to the probability to kill people on ground (G0A), which is directly linked to the Flight Termination System – FTS;
- Reliability during ground and flight phases.

To take into account the arrival of micro/mini-launchers at CSG, [2] and [3] need to be updated. This process is currently ongoing and will allow, for example, to take into account the return phase of the reusable launcher in the quantitative requirements.

3.1. *Safety during ground operations with regard to regulation*

New architectures and simplified concepts of operations are proposed by the micro-launchers, particularly in the context of high launch rate and reusability. However, they have to comply with specific rules on the ground declined in [3], concerning the facilities, the associated equipment and the launcher operations during its entire lifecycle on ground. As opposed to the launchers already operated at CSG, the reuse concept requires to introduce the following phases on ground: landing, return to safe-state (see Figure 3), mechanical recovering and finally maintenance & repair operations.

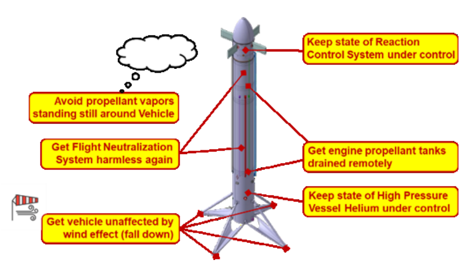

Fig.3. Example of Safing functions after landing

After landing, the vehicle state must be known and mastered before getting any staff access authorization. This point is a challenge for CNES, as the vehicles will not be wired to the control bench after the flight (see document [6]).

All the previous operations and associated hazards require to be categorized at RAMS (Reliability, Availability, Maintainability and Safety) level. For example, to ensure the reliability of the FTS from one flight to another, RAMS analysis need to increase the life cycle profile and take into account preventive/predictive maintenance of the system.

With the New Space context, the tendency is to consider "eco-responsible" launchers. As a consequence, the micro/mini-launchers projects try to innovate increasingly by using different kind of propellants, some with low ecological impact (such as bio-methane, that could be potentially produced locally in French Guiana (see document [7]) and not dispersing particles in the stratosphere. For many of them, the usual cryogenic propellants such as liquid Oxygen coupled to liquid Hydrogen (LOX/LH_2) or Kerosene (LOX/RP-1) are now replaced by hazardous products such as liquid Methane, Nitromethane, Hydrogen Peroxyde (H_2O_2), and even hybrid propulsion based on the combination of cryogenic and solid (polymers) propellants. Their introduction creates new failure modes and risks which have to be, under safety aspect, analysed, modelised and taken into account during their implementation at CSG. For some, the risks are clearly reduced compared to the products already used on site but for others, additional constraints linked to their intrinsic characteristics (self-ignition, pyrotechnic or pyrophoric effects) may be imposed to the projects at CSG (for example pyrotechnical accreditation, permanent monitoring of pressure/temperature with on-duty constraints).

The introduction of a multi-launchers Launch Base has an important impact on the organization and management of the coactivity. Indeed, even if several launchers are already operated from CSG, each launch pad is specific and they are far enough from each other to be considered as independent (no safety impact on each other, but simultaneous operations activities possible except on launch day). In the micro/mini-launcher context, it will not be the same configuration (see document [4]) because the plan is to build a multi-launchers Launch Complex (under CNES responsibility) capable to host up to 5 micro/mini-launchers and one demonstrator campaigns (Callisto, see [6]) at the same time. After Callisto campaign, its ground means could be reused by additional micro/mini-launcher Of course, it is understood that every project will have to operate their launchers in compliance with all specific rules mentioned in REI [3], a particular and consistent analysis has to be performed to ensure that all the separate risks have been considerate and/or mitigated at project level but also at global ELM level. For example, lightning protection, submitted to French classified facilities and environmental legislation (ICPE), will require a specific analysis for each project. However, all results will be subject to a global synthesis to ensure safety consistency at ELM level.

Thus, all the hazardous effects areas of each projects have to be calculated and modelised, according to the requirements of the order [8]. For example, thermal or overpressure effects caused by the explosion of a tank during the preparation or the complete vehicle on the launch pad. The potential impacts (and associated constraints) of each project on another (domino effects) have to be identified, discussed and accepted, based on a shared strategy.

As mentioned above, the introduction of reusability part (launchers are called RLV for Reusable Launch Vehicle, see article [9]) has not only a direct impact on the layout but also on the global operational and safety logic. From then, the launch complex requires to include landing zones on ground (return to landing site mission) or at sea (down range mission). In any case, these areas should be safe but accessible and equipped enough to ensure all the after-landing operations, particularly the remote back-to-safe mode of the launcher. An option under consideration, is to use robots for power, data harnesses and fluidic connections, which will be useful to manage short-term risks after landing.

3.2. *Launcher Safety and Reliability during flight with regard to regulation*

Regarding Safety and Reliability during flight (MSI only), the REI [3] has two main qualitative requirements:

- At Flight Termination System level (FTS - system that terminates the launcher flight in case of failure), Fail Operational is required. It means that FTS needs to be redounded and its chains to be geographically segregated on the launcher in order to be operational after one

failure (which can be caused by external aggression) in case of need;
- At Launcher level, Fail Safe /Fail Safe is required. It means that after two independent failures (first on the launcher, then on the FTS), the FTS still has to be operational and the safety is ensured

Furthermore, Technical Regulation [2] requires that the probability to have human casualty (sum of all risks with catastrophic consequences) must be lower than 2.10^{-5}. The FTS is a one of the contributor but there is also the contribution of the debris/stage of the launcher, re-entering atmosphere post orbitation. In order to manage the risks inherent to the launcher and ensure safety during flight phase, the operator will have to conduct a Hazard Study (Article 7 of [2]). This risk analysis will address all the feared events with Safety impact and manage them with the appropriate mitigation means. It is the role of the CSG safety submission and launcher conformity processes, under CNES validation.

The architectures proposed by the micro-launchers, simplified in order to gain mass (mostly simplex functional avionic), and innovative (new type of propulsive or navigation systems), may result in an increase of the risk to have a failure of the launcher during the flight, impacting the safety.

The Reliability of the FTS should be consistent with the reliability of the launcher. As a consequence, the design of the flight termination system is even more important than before. It is a mitigation mean, mandatory by the [3], and used to protect the population on ground in case of failure of the launcher.

If using telemetry and localization chains on board of the launcher (as part of the FTS), the equipment's need to be compatible with the ground means from the CSG.

New technologies are also emerging, especially regarding the localization (safety) and navigation (functional) functions. The use of GNSS (Global Navigation Satellite System) in complement of inertial measurement for the functional chain will bring risks to be tackled (availability of the satellites, protection against spoofing or jamming of the signal, atmospheric phenomenon). These scenarios of failure will have an impact on the reliability of the navigation system (functional and safety) and therefore on the reliability of the launcher. They must be taken into account in the Risk Analysis using for example return of experience from KASSAV-1 project (see [10]). What's more, commonality between functional and safety equipment on the launcher (for example using same GNSS system), will impact the compliance to the FS/FS criterion because it may create a dependence and therefore a common mode between functional and safety chains (which has to be avoided by [3]).

The use of pyrotechnic equipment to terminate the launcher when needed (in case of failure of the launcher leading to loss of the mission) is the historical approach to ensure correct fragmentation of the launcher. It impacts the mass of the launcher and complicates the integration of the equipment's with regards to the safety of the operators on ground. An alternative type of neutralization is increasing; the engine's stop that cut the thrust of the engine and enable to control the fall back of the launcher in the sea. This method impacts safety studies, the fragmentation model used at CNES and the correct mitigation of the risk on the population (depending on the launcher aerodynamics). Indeed, cutting the engine have residual effect/risks that need to be identified and managed in the scope of the risk analysis: residual thrust of the engine, time reaction compared to the pyrotechnic systems (high velocity propagation of a detonation). There are trades-off to be done on the neutralization's logic in order to safely manage the fall-out of the launchers' debris during the MSI.

3.3. *New RAMS reflections at CNES*

To remain in the dynamic of low cost, high launch rate, reduction of weight and high profitability, the micro/mini-launchers projects tend to introduce commercials off-the-shelf (COTS). Indeed, using COTS (such as general public pressurized tanks, electrical pumps, electro-mechanical actuators and valves, etc.) has significant advantages in terms of cost and development time and often have proven track records in commercial products (warranties, available from multiple sources, quick improvement of the technology, high reliability based on mass production and return of experience). By introducing COTS, the micro/mini-launchers sector can definitely take the advantage of the newest technologies being used by the manufacturers. However, despite the advantages of using these equipments, they should not be employed without fully understanding their implications in a rocket engine environment. A dedicated European standard, ECSS-Q-ST-20-10C, related to Off-the-Shelf items utilization in space systems already exists [11] but is more oriented to the re-use of products developed for previous space programs. It also focuses on the management process within development (identification, characterization, selection, procurement, qualification). To ensure the compliance with the specific rules mentioned in [3] (for example, safety factors coefficients, qualification and proof-testing process of the on-board fluid systems) and also to ensure a good level of reliability, a reflection is currently conducted mainly on the qualification and acceptance process of these equipment, particularly when they are involved in sensitive functions. It leads to the need to include in the logic of development of the launcher, the potentials derisking, delta-qualification and additional acceptance tests to be performed in order to validate their reliability in the scope of the mission.

Unreliability, at launcher level, is directly calculated by the industrial responsible of the launcher. It is a bottom-up approach consisting in summing all the products and subsystem theoretical unreliabilities with the appropriate logic (it depends of the architecture). This method is accepted and is used as it to demonstrate compliance to the RT (see [2]). However, it has a principal inconvenient; it is very optimistic compare to the reality.

The worldwide return of experience of space launchers, even more since few years (with lots of American & Chinese launchers), allows to have a more realistic approach in calculating the unreliability of a launcher. This calculation method would be based on "observed" unreliability (described in the Flight Safety Analysis Handbook, see document [12]), instead of theoretical, with data coming from comparable launchers (comparable in terms of type of propulsion, staging, size of payload for a type of mission). It is firstly used for the assessment of the unreliability of the first two flights of a new launcher and is based on a binomial distribution law with a confidence level of 60%. This figure is improved by taking into account also the theoretical assessment or requirement made by the industrial. This method is applied to calculate the launcher mission unreliability but could also be applied only on a specific stage or phase of the launcher.

From then, and for the next flights of this launcher, the Bayesian approach allows, in addition to the first approach, to consolidate the figures from flight to flight with the launcher's own data. The objective is to take the correct weight factor between its own data (with its own failure if any) and the data from comparable launchers.

Those kind of assessments would lead to degraded unreliability figures but more relevant with regards to feedback from previous launcher's flights. Mission reliability of micro/mini-launchers, difficult to express as for now, should be lower than the institutional ones (Ariane & Vega). The feedback from comparable launchers in the world shows that the unreliability could be around 5.10^{-2} / 10^{-1} per MSI.

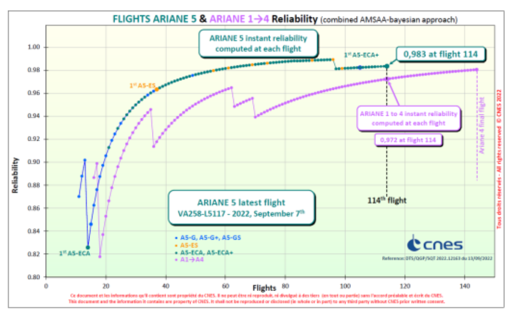

Fig.4. Ariane 5 & Ariane (1 to 4) flights reliability

4. Space debris mitigation

4.1. *Description of satellite End-of-Life operations*

The satellite EoL operations include the following steps:

(i) Satellite deorbitation or reorbitation to liberate the orbits mostly used:

- If the implementation is done in protected GEO regions: the satellite withdrawal operations must be such that it cannot return to the protected area naturally within 100 years;
- If the implementation is in the protected LEO region: these operations must be such that it

must no longer be present in LEO region within 25 years after the end of the mission.

(ii) The fluid passivation of the satellite: It corresponds to the emptying of the propellants and to the depressurization of all the pressurized systems present in the satellite, such as the chemical propulsion systems and plasma too. At the end of the fluid passivation, the resulting pressure must not exceed a few bars.

(iii) The electric passivation of the satellite: It corresponds to the definitive de-energization of all systems and equipment of the satellite that could either present risk for the integrity of the satellite or disturb other orbital objects. This includes:

- The shutdown and isolation of all actuators (Attitude and Orbit Control System) such as reaction wheels or gyroscopic actuators;
- The shutdown of all equipment capable of transmitting RF;
- The disconnection and isolation of the battery and of all other sources of electricity generation (solar generator for example).

4.2. *Regulations and standards*

4.2.1. *French Law on Space Operations*

More specifically about EoL operations, the law [1] stipulates that: “The probability of being able to successfully carry out the withdrawal operations must be at least 0.85. This probability, which does not include the availability of consumable energy resources, must be calculated before the launch over the duration of the control phase for which the system has been qualified and takes into account all systems and equipment usable for these maneuvers, their possible redundancy levels and their reliability”. The respect of this law is required to obtain the right to launch a satellite from CSG or to operate a satellite from France.

An update of the RT [2] is going on this year, with a possible reevaluation of this value to 0.90, as this issue becomes more and more important for the future of space traffic management. The requirement is even stronger for a constellation of satellites: 0.95 for a satellite in a constellation bigger than 50 satellites. Furthermore, for the LEO orbit the requirement of 25 years for the atmospheric re-entry is about to become five times the mission duration of the satellite to encourage longer missions with better quality.

4.2.2. *International standards on Space Debris Mitigation*

The general goal of Space Debris Mitigation is to reduce the growth of space debris by ensuring that spacecraft and launch vehicle orbital stages are designed, operated and disposed of in a manner that prevents from generating debris throughout their orbit lifetime – with the main objective of insuring space sustainability for the future.

France is the only country to have a space law, but the Inter-Agency Space Debris Coordination Committee (IADC) and the International Organization for Standardization (ISO) released Space Debris Mitigation guidelines and requirements few years ago.

More specifically about EoL operations, in the ISO 24113 of 2019 on Space Debris Mitigation (see [13]), the absolute probability of successful EoL operations is set at 0.90 and a “Specific criteria for initiating the disposal of a spacecraft shall be developed, evaluated during the mission and, if met, consequent actions executed.”

4.3. Probability of successful End-of-Life operations

The probability of successful EoL operations corresponds to the reliability of the chain of subsystems required to perform the operations. Before the launch, it is calculated over the mission duration. The reliability engineer conducts it in interface with project architects and usually follows the next steps:

- Identifying the EoL operations necessary for the studied satellite;
- Identifying the subsystems necessary to fulfill these operations;
- Evaluating the failure rates of these subsystems;
- Calculating the overall reliability of this chain of subsystems;
- Enriching the result with experience feedback, if available.

The theoretical reliability assessment of a satellite is based on the hypothesis that its components are in their qualification area and have constant failure rates λ over the mission duration and independent failures. The exponential law is used to calculate the reliability.

However, the results of this method are often pessimistic regarding with the real performances of the satellites. Indeed, the main source of uncertainty of the method comes from the reliability handbooks. In Space industry, the Military Handbook on Reliability Prediction of Electronic Equipment (see [14]) is the most widely used empirical reliability prediction model for electronic equipment in Space industry. However, it has not been updated since 1995, and is incomplete since new components, technologies and quality improvements are not covered. Some R&T had been conducted by the French space agency and Space industrials – Airbus Defence & Space and Thales Alenia Space – in order to update and revitalize this standard in recent years and a Reliability models extensions user Guide has been published (see [15]). The more recent FIDES [16] reliability handbook has also started to be used in Space industry for few years, and CNES is currently upskilling on the handbook.

Mathematical models based on experience feedback are used to improve this forecast estimate of the reliability:

- Bayesian model: It takes into account the effective operating life of identical subsystems, operating in similar environments and conditions of use (including temperature) to improve the forecast reliability assessment;
- Chi-Square model: The reliability is only based on empirical feedback – composed of tests or in orbit data. This model is only useful when many subsystems operating data is available – for satellite constellations using the same platform for example. When the total operating time is small, the estimation is pessimistic and not reflecting the reality.
- Arrhenius model: It is used to update the subsystem failure rates during the satellite lifetime by taking into account the real operating temperatures.

4.4. Mission extension

Currently on CNES satellites, the probability of successful EoL operations is evaluated before the launch – in order to obtain the authorization to launch the satellite, and at the end of the nominal mission – in order to obtain the validation for a mission extension.

The French Space Agency is currently updating its regulation and a re-estimation of this probability taking into account the failures and anomalies seen by the satellite during the nominal mission will be required in order to obtain a mission extension for all French operators. The same criteria of a probability higher than 0.90 will be used to obtain the mission extension authorization. This probability of successful EoL operations – along with the remaining propellant mass – therefore constitutes one of the principle criteria to choose the best moment and guarantee with the best estimate possible the operations of passivation and withdrawal from service for satellites at their EoL.

5. Conclusion

Main objectives for micro/mini-launchers are to maintain a high launch rate and to reduce cost at maximum. It has an impact on the choice of design for their launchers and on the concept of operations on ground, even more in the context of reusability. The challenge of CSG is to help each of them to achieve their objectives while always ensuring safety (on ground and in-flight) during their entire life-cycle.

The necessary evolution of the FSOA [1] and its associated decrees and application rules is currently the object of a reflection at the French Space Agency and its responsible ministries. The update should give the micro/mini-launcher projects a clear and stable regulatory framework, necessary for the sustainability of their activities, without degrading the safety for people, launch base complex facilities and environment at CSG.

Satellite successful End-of-Life operations and compliance to international Space Debris Mitigation requirements are also issues of importance for CNES. As part of the RT [2] update, CNES is ready to propose new standards internationally. Indeed, being able to dispose a satellite in a safe and reliable manner has a fundamental importance in order to limit the exponential proliferation of space debris in already crowded orbits.

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