DE-ORBITING THE INTERNATIONAL SPACE STATION ISS: SAFETY CONSIDERATIONS AND PRELIMINARY ANALYSIS

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ABSTRACT

NASA has proposed to its partners the de-orbiting of the International Space Station (ISS) around the year 2020. Technical plans on how to do it have been presented as long as the year 1999. The current situation of ISS claims for a possible extension of the date of 2020 but to all International Partners is clear that the de-orbiting operations need to be performed with safety as the main and central paradigm. The proposed paper evaluates several scenarios and options for the de- orbiting of ISS. The paper proposes trajectory design considerations, de-orbit strategies and the calculation of casualties and fatalities for some of those. The paper proposes as well some fragment disposal regions using the classic approach of disposing ISS on ground and compares it with the feasibility and cost with the approach of end of life vehicle recycling culture of the European Union. The paper computes and calculates the reliability of all options and establishes a trade-off between all of them. The paper provides a detailed mathematical model that is able to calculate casualty and fatality rates. The mathematical model has been programmed in the ASTOS software tool and the corresponding casualty and fatality curves have been computed for some considered options. The following options are studied, discussed, and traded- off: simple one-go complete disposal of ISS with controlled de-orbiting using a service module, complex partial disposal of ISS elements with controlled de-orbiting using a modified version of service module, same variation using a set of auxiliary vehicles, design of a new vehicle to dispose the ISS and finally the uncontrolled re-entry of the entire ISS. Further, the paper proposes some de-orbiting requirements, and mission design considerations for a successful end-of-mission closure.

1. LIFE CYCLE OF ISS: OPERATIONS AND END-OF-LIFE

In 1994, President Bill Clinton re-launched the space station project following the break-up of the Soviet Union and the Eastern Block. Giving it a new name, International Space Station Alpha, President Clinton pressed on for it to be a symbol of post-Cold War co-operation.

Figure 1. ISS completed in 2003

Already prior to the launch of the first module, NASA proposed to its partners the de-orbiting of the International Space Station (ISS) around the year 2016. Technical plans on how to achieve this have been presented as far back as 1997. Although the current situation of ISS claims for a possible extension of the

date of 2020, it is clear to all International Partners that de-orbiting operations need to be performed and this with safety as the main and central paradigm.
The challenge in de-orbiting the ISS comes both from its large mass and inertia moments around its axes, and from the large area that undergoes disturbance forces.
The ISS has a mass above 409 metric tons, distributed over 3 Russian modules, 3 American modules, one Japanese and one European module plus tons in metal trusses and solar panel arrays. With a length of over 51 meters in velocity direction and a 'width' of 109 meters (H-bar) it is the largest, heaviest human-made space object. Its frontal area reaches almost 1000m^2, and if constructed on Earth it would fully cover the field of an NFL team.

Module Length: 51 meters
Truss Length: 109 meters
Solar Array Length: 73 meters
Mass: 409 metric ton
Habitable Volume: 388 cubic meters
Pressurized Volume: 916 cubic meters
Power Generation: 8 arrays (84 kW)
Lines of Computer Code: ± 2.3 million

Figure 2. ISS, facts and figures

In order to understand the extend of this object, some comparisons could be used: the pressurized volume of the ISS is similar to a Boing 747 internal volume; the mass is equivalent to more than 320 automobiles and most important it is almost four times as large as the MIR: the biggest object deorbited so far.
In is important to perform considerations on the materials that compose the ISS. The big power truss that holds the solar panels is made of aluminium, a material that normally does not survive the re-entry. Several other components are instead made of Iron, Beryllium, Chromium, graphite ceramics and titanium; these are good candidates for the list of survival fragments.

2. CANDIDATE DE-ORBIT SERVICE MODULES

Currently there is no one vehicle that has been specifically designed for the purpose of de-orbiting an existing space system, especially of the size of the ISS. However, there are servicing modules which have been created for the purpose of reaching the station, docking/berthing to it and, in some cases, perform orbit maintenance.
The following table shows a list of operational and future operational vehicles for the station servicing.

2.1 Automated Transfer Vehicle (ATV)

Available propellant: 4700 kg (+510 for own de-orbitation)
Thrust: 2014 N (4 x 503.5 N)
Isp: 310 s

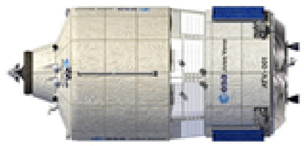

Figure 3. European ATV

2.2 H II Transfer Vehicle (HTV)

Available propellant: 2400 kg
Thrust: 4 x 490 N
Isp: 310 s

Figure 4. Japanese HTV

2.3 Progress M

Available propellant: 1700 + 250 kg
Thrust: 6190 N
Isp: 326 s

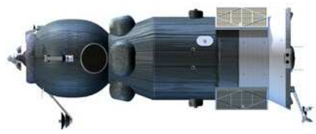

Figure 5. Russian Progress M

2.4 Dragon

Available propellant: ?
Thrust: 4 x 400 N (inclined)
Isp: ?

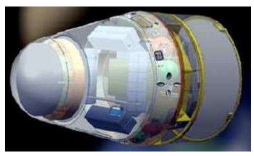

Figure 6. SpaceX Dragon

2.5 Cygnus

Data not available.

2.6 Service module selection

The most critical aspects for the de-orbit of the ISS is the thrust level and the propellant loading, therefore these are the criteria for the selection of the most convenient service module.
The Progress M presents the highest level of thrust, but the propellant mass is not sufficient: it was at the limit for the MIR de-orbit and the ISS is four times heavier.
The ATV presents the best compromise between the available service modules and it will be investigated in the scenarios of chapter 5.

3. PAST DE-ORBIT STRATEGY

3.1 UARS re-entry, uncontrolled

An uncontrolled re-entry is a passive strategy: we accept the risk of a low casualty probability. This approach is followed every time a satellite is no more controllable (UARS) or when the propellant on board is not enough to perform a de-orbit manoeuvre. In these years (2010-2112) the solar activity has its peak, this produces an expansion of the Earth atmosphere causing the increase of the natural decay effect. The UARS and the German ROSAT are two examples. Both of them re-entered over not populated areas causing no casualties or damages to goods.

3.2 MIR re-entry, partially controlled

In 2001 the MIR has been deorbited in a partially controlled way: the natural decay effect reduced the orbit altitude to 220 km. During this period the MIR station was in contact with ground stations and the attitude was controlled to avoid any tumbling motion.
A Progress M vehicle was used for the active de-orbit part: three burns were required to reduce the perigee altitude to 80 km altitude and direct the re-entry over the South Pacific ocean. The intermediate orbit was not fully stable (perigee altitude of 165 km) and the long last burn duration (20 minutes) created some concerns in the aerospace community, but the success was achieved.

3.3 ATV re-entry, fully controlled

The controlled re-entry of ATV created a concern among ESA and CNES officials in what respect to casualty and fatality figures. In September 2008 ESA initiated a series of detailed studies to accurately compute these figures and the corresponding ground risk foot prints. The results obtained by the Technical Directorate of ESA used state of the art mathematical models that have been independently verified and validated. ATV broke into approximately 600 main fragments and many other much smaller.

Figure 7. ATV fragmentation

The Automated Transfer Vehicle was designed to end its mission by a destructive re-entry using the earth atmosphere. The de-orbitation scenario started with the departure of the vehicle from the ISS followed by a drift period to phase with the targeted impact area. Once this phasing was finished ATV performed two de-orbitation boosts which caused it to enter the atmosphere and started fragmentation by aerodynamic and thermal loads. ATV Jules Verne re-entered Earth on September 29th 2008 ending a very successful first mission for ESA and its partners. The first de-orbitation burn (see figure 8) changed the ATV orbit from circular to highly elliptical while the second one targeted Zero-altitude periapsis and subsequent collision with Earth.
ATV was composed of two main parts: the spacecraft subassembly, and the integrated cargo carrier. ATV used four solar arrays skewed about 45 degree for power and communicated via a S-band antenna mast. The materials list of which the subsystems of Jules Verne are made represent about 100 different collection types: from Titanium to Aluminium, from Beryllium, to carbon fibre, etc. The total length is about 10 meters while the total diameter is about 4.5 meters.

To study ATV re-entry safety in depth, ESA and CNES constituted a task force in spring 2007 with experts and engineers from both Agencies.

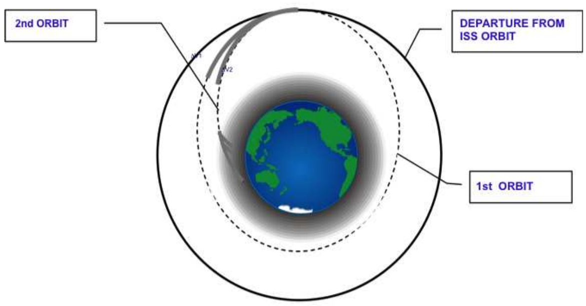

Figure 8. ATV de-orbit strategy

The task force recommended to perform a detailed risk analysis for the re-entry phase of Jules Verne and the evaluation of the casualty and fatality probabilities versus the acceptable standards.

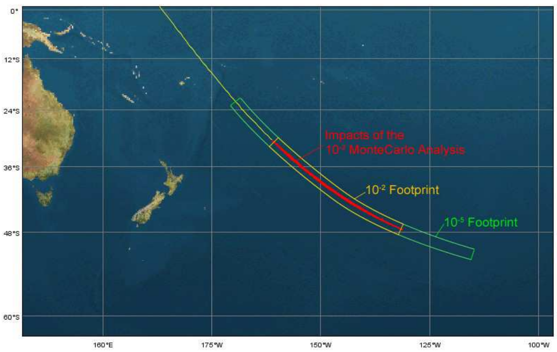

Figure 9. ATV footprint from ASTOS

At this point in time, commanded by the ATV Re-entry Safety Panel and via ATV operations team, the Technical Directorate of ESA started to work in the risk analysis while the Operations Directorate team supported the Panel in an independent verification of the work of ESTEC. ESTEC assessed the final ATV disposal cargo list w.r.t. their contribution to the surviving fragments list in the case of an uncontrolled re-entry. And it computed several trajectory types with their corresponding casualty and fatality risks. All in total, ESTEC ran about 20 million of trajectories in two analysis phases. The trajectories varied six parameters: the duration of the last impulse burn, the level of the thrust, its angle, the density of the atmosphere, the altitude of the explosion, and the direction of the ejection of the fragments.

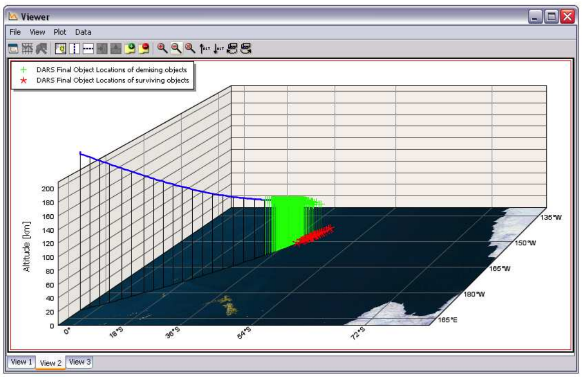

Figure 10. ATV fragmentation in ASTOS

4. SIMULATION TOOL

ASTOS [1] is a simulation and optimization environment to simulate and optimize trajectories for a variety of complex, multi-phase optimal control problems. In the last twenty years it has been successfully applied in several industrial or ESA projects in the field of launcher, re-entry and exploration missions. Just to provide some examples the following projects can be mentioned: Ariane5, Vega, ATV, Hopper, Skylon, Flyback Booster, X38, Capree, ATPE, USV, Smart-Olev, LEO, Astex, IXV, ARD, Expert, et. al.

ASTOS consists of fast and powerful optimization programs, PROMIS, CAMTOS, SOCS and TROPIC, that handle large and highly discretized problems, a user interface with multiple-plot capability and an integrated graphical iteration monitor to review the optimization process and plot the state and control histories at intermediate steps during the optimization.

ASTOS comprises an extensive model library [2], which allows for launcher and re-entry trajectory simulation and optimization without programming work.

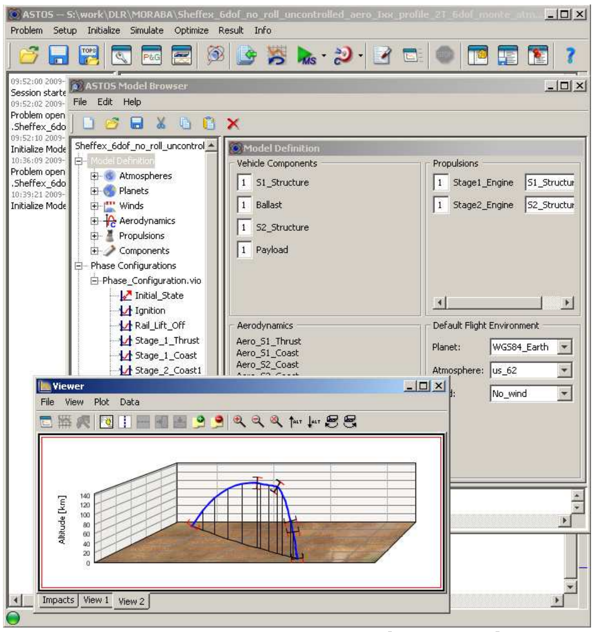

Figure 11. ASTOS 7 screen-shot example

4.1 Risk computation

For on-ground risk assessment ASTOS comprises modules for destructive and non-destructive re-entry simulation. These modules compute location, mass, size and final velocity of the surviving fragments. From that a safety analysis module computes casualty and fatality probability for the re-entry event using a population density model. Simple models based on user-defined ballistic coefficients or drag coefficient tables can be

used within a trajectory optimization. These models may also be used to restrict the instantaneous impact point of a launcher ascent. More sophisticated approaches containing fragmentation and explosion models are available for simulation and analysis only.
Based on the final geometry, kinetic energy and on the calculated impact points, the risk for humans due to each individual object and an overall risk value is computed. Besides the risk for people on-ground, an assessment for the imposed risk for planes and ships are provided. In the following the assessment approach is detailed.
Based on the trajectory and the final geometry of each fragment a casualty cross sections is calculated [4]. The on-ground risk calculation is based on the GPW V3 population density model [5]. Population growth is considered by an exponential growth rate assumption. The calculation of risk values is similar to the method described in [6]. More detailed information can be found in [7], an example of the air traffic data is presented in Figure 12.

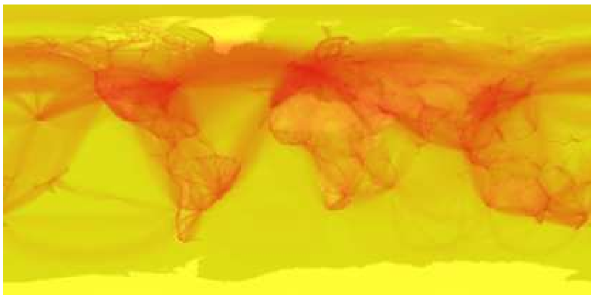

Figure 12. Air traffic density in ASTOS

5. END-OF-LIFE SCENARIOS

The ISS is in a circular orbit with an altitude varying between 350 km and 450 km. Due to residual atmosphere the station encounters a drag force that naturally reduces its orbital energy. When the station reaches the end of its operational life, orbit maintenance ("re-boosting the station") will probably cease. Without any intervention the ISS will slowly decay and eventually re-enter the atmosphere, burning on its way down and eventually impacting the surface.
At the disposal phase of the ISS there are thus two options for the ISS operators: either to leave the station in its place, or to take an active role in its disposal. The following scenarios can be invoked:

I. Uncontrolled re-entry through natural decay
II. Leaving the station to naturally decay to a lower altitude, then undertake an active final de-orbit with one or more 'de-orbit service modules'
III. Dispose of the ISS through a fully active de-orbit strategy, using several 'de-orbit service modules' to de-orbit the ISS in one piece
IV. Dispose of the ISS through a fully active de-orbit strategy, using several 'de-orbit service modules' to de-orbit the ISS in several pieces
V. Take a 'recycling approach': retrieving ISS elements to be post-processed on ground
VI. De-orbit the station in one piece with only one new 'de-orbit service module' designed from the ISS de-orbit safety requirements

When planning for end of life measures, it is also necessary to take into account system design considerations (e.g., maximum continuous operational time of thrusters, structural load demands, etc.), fragment foot-prints for the different options, calculation of casualties and fatalities, development and ground operation costs.

5.1 Scenario I. Uncontrolled re-entry through natural decay

The propellant mass required to maintain the ISS in its altitude range is very high; the main reasons are a relatively low working orbit associated to a high frontal area. The design of such a demanding orbit was driven by the fact that the Space Shuttle was limited to an orbit altitude of around 400 km.
When considering the ISS characteristics the natural decay due to drag will lead to a re-entry in 2-4 years, depending on the solar activity of the year of consideration: respectively 2 years in 2020 and 4 year in 2028.
A re-entry model of the full ISS has not been performed in this preliminary analysis, but some educated considerations can be evaluated from a comparison with a known model, ATV. The expected foot print will be longer than ATV due to a higher average ballistic coefficient, moreover the foot-print will be more "densely" populated with debris (the initial mass of ISS is 34 times the initial mass of ATV).
The uncontrolled re-entry could be anywhere over the Earth surface between the latitudes of -51 and +51 degree, therefore a scaled average population density is used to compute the risk associated to this event. For the computation it should be considered that the Earth population is increasing. A low survival rate (20%) due to high presence of not thermal resistant materials, yet this would still leave a casualty area around 3700 m^2. This would lead to a casualty probability of $7.3 \cdot 10^{-2}$, or

1 in 14. Evidently, this risk is too high to be acceptable, and therefore the solution to let the ISS perform an uncontrolled re-entry would be irresponsible.

5.2 Scenario II. Natural decay complemented by a service module

It is possible to let nature perform part of the work, and take advantage of the natural orbit decay of the station. Letting the ISS' orbital altitude decay from 400 km down to 220km would take between 2 to 4 years (solar cycle dependent). If orbital decay is allowed, the ISS could be utilized until a minimum safe operation altitude is reached, at which point the astronauts could not be maintained anymore on board. From that point on, the ISS would officially end its function as an inhabited space laboratory. During its natural decay, it would be necessary to manage the ISS' attitude, such that it can correctly be controlled in the active de-orbit phase. This leads to costs in attitude maintenance (propellant), and operational costs for an 'empty' station. On the other hand, it would be possible during the last mission to attach a last set of internal and external payloads that can be monitored from ground, still yielding some return until the final de-orbiting of the station.
Once in 220 km orbit, a series of burns need be performed to lower the periapsis altitude such that the ISS re-enters within one orbit. There are two possibilities. Firstly it is to perform the same strategy as with ATV, bringing the Periapsis down to 0 km, making sure that ATV with collide with the Earth's surface independently of aero-thermodynamic effects. The second possibility is to lower the perigee just enough to an altitude within the atmosphere such that the atmospheric drag will surely slow down and break up the station for it to fall on Earth. This was the MIR station de-orbit strategy. The de-orbit burn needed to reduce the periapsis to 80 km altitude requires around 5000 kg of propellant and 6-7 burns of 20 minutes by an ATV vehicle. The high number of burns is due to the long thrust necessary and the low efficiency of long burns. Bringing the Periapsis down to 0 km would require 9000 kg of propellant. This second strategy would slightly reduce the footprint (from 1800 km to 1700 km) and most important will reduce the risk that parts of the ISS will skip and re-enter after one orbit.
Figure 13 presents the impact footprint of the two final orbits analysed: the 220 x 80 km altitude in red and the 220 x 0 km altitude in brown. The nominal impact is identified by a star, whereas the two triangles identify respectively the low ballistic coefficient fragment (3 kg/m^2) and the high ballistic coefficient fragment (5000 kg/m^2).

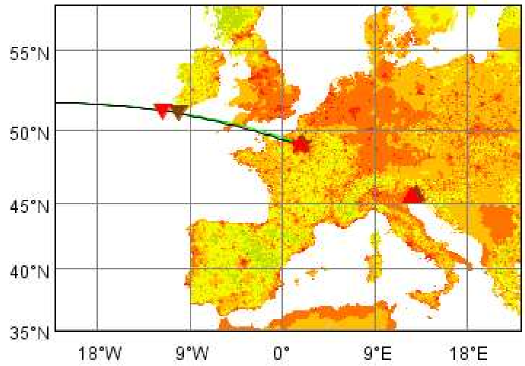

Figure 13. Impact footprint of two orbits with different perigee altitude (80 km in red,0 km in brown)

In Figure 14 the final part of the re-entry is plotted; in red starting from a 220x80 km altitude orbit and in brown starting from a 220x0 km altitude orbit. The red trajectory presents a high risk of skipping at around 100 km altitude.

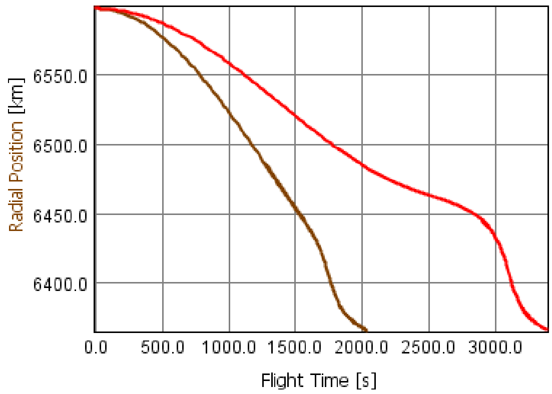

Figure 14. Radius evolution of two orbits with different perigee altitude (80 km in red,0 km in brown)

However, it would be disadvantageous in terms of de-orbit service module, because ATV is not designed to bring 9000 kg of propellant. Therefore there would be a need for either a modification of ATV or two ATVs docked to the ISS; since the intermediate orbit will not be stable due to the low periapsis altitude.
One of the main disadvantages of this scenario is that it counts for the availability of ATV beyond 2015. Currently the ATV programme is not scheduled to be operational then, however, if programme knowledge and tools are retained it would be possible to resume ATV production beyond 2020.

5.3 Scenario III. Fully active de-orbit

The consideration to be taken between performing a fully active de-orbit or to naturally decay the station lies

between the costs of building and operating several ATVs to lower the station's altitude in a controlled way and the 'empty' ISS maintenance and ground operations costs for at least 2 years.
If the same altitude change (from a 400km orbit to a 400x0km orbit) had to be achieved through an active strategy by means of ATV, 16 tons of propellant would be required. This amount of propellant cannot be brought up by one single ATV. As a result, several ATVs (3 to 4) would be necessary to lower the station, with all the ensuing production and operations costs. Moreover, each ATV would need to perform 5 to 6 burns before undocking and de-orbiting themselves: the maximum single burn duration is around 20 minutes. Furthermore, multiple ATVs need to be in operational status due to the short decay time of intermediate orbits, therefore also relying in the capacity to have several exiting ATVs at the same time (storage costs due to production time), the capacity of having multiple ATVs docked to the station, and the capacity to launch so many in a very short time (high costs due to multiple launches, fast production rate of Ariane 5s and orbit maintenance of ATVs until docking with station). Even if this scenario can be achieved, the risk of the entire de-orbiting operation is quite high due to a) the number of orbital manoeuvres to be performed with a high number of vehicles and b) the number of de-orbits to be performed (ISS + 5/6 ATVs).

5.4 Scenario IV. Fully active de-orbit in several parts

An alternative to the de-orbiting of the massive ISS, would be to 'cut' the station into pieces and de-orbit them individually. This strategy would permit an easier disposal of smaller masses (shorter duration of de-orbit burns, less risk in attitude control during de-orbit burns). It would permit using servicing modules carrying less amount of propellant or less propulsive thrust than ATV, eliminating the problem of ATV production past 2020. Also, this would reduce the footprint on ground every time a part goes down, decreasing constraints on the targeted impact point to be chosen. This would also create the flexibility to use different servicing modules in order to dock/berth to both Russian and American ports.
However, this scenario has various disadvantages. Firstly, there is a limited number of docking ports available to which the vehicles can attach to. There is thus a need to detach parts of the ISS that cannot be docked to first and in a certain order, i.e. solar panels, work trusses and radiators, etc. This means that a robot arm capable of disassembling these parts must be present, and probably the presence of human operators is required for this complex task. However, the ISS needs such structures to properly function; there could be the temporary situation that the station would not be controllable during this long process. Furthermore, a high number of de-orbit vehicles is necessary to perform de-orbit operations, and due to complex shapes, the attitude control during de-orbit manoeuvres may be not achievable.

5.5 Scenario V. De-orbiting ISS by recycling

To solve the problem of de-orbiting irregularly shaped parts and to reduce risk to the population, the original 'space shuttle' strategy could be considered. A visiting vehicle that is able to re-enter the atmosphere with no destruction could allocate modules and parts of the ISS into its cargo bay, in the same fashion as the Space Shuttle did. The main advantage is the recovery of high valuable materials and data from the ISS and the reduced pollution of the Earth environment.
However, after the retirement of the Shuttle there is no vehicle with such extended capability. At the present time the Soyuz can accommodate a small volume and 500 kg of mass. The SpaceX capsule Dragon is designed for 3000 kg of down-mass [3] with the second demo mission coming soon. Even with Dragon the available volume is reduced and the objects should be transferred via the docking port (max length 1.3 meter).
Europe planned the Advanced Re-entry Vehicle (ARV) with a cargo capability of 1500 kg mass with the same limitations of Dragon in terms of volume and dimensions.
This scenario even if highly appealing requires either a high number of service module (140) with limitation on the dimensions or a new vehicle with a cargo bay comparable to the Space Shuttle.

5.6 Scenario VI. Design a new service module

The single service module presented in chapter 2 is not able to fulfil the requirement of an active scenario (scenarios II and III). Therefore another option could be to design a vehicle (from screech or modifying an existing one) to specifically de-orbit the ISS.
The requirements on such a vehicle would be: a) to have a docking system compatible with the ATV port in order to thrust aligned with the ISS centre of mass; b) a high Isp engine as provided by a cryogenic upper stage to reduce propellant required; c) a high thrust level to reduce burn duration ie minimize losses and risk (higher than 50 kN); d) to be re-ignitable, at least two burns for the de-orbit strategy.
It should be noted that these requirements are similar to the performance provided by the Ariane's ESC-B stage with Vinci motor to lock with the payload adaptor to an

ATV docking port. This would give the capability to thrust with 180kN, Isp of 465s and a propellant load of 25-30 metric tons.
The de-orbit strategy could be performed through two classical manoeuvres:
a) Lowering the periapsis to 220 km altitude, it requires 4700 kg of propellant, 2 minutes burn.
b) Lowering the periapsis to 0 km altitude, it requires 6000 kg of propellant, 2.5 minutes burn.
This would permit a fully controlled de-orbit of ISS with one service module (and one single launch of Ariane 5).
To perform this, there are several issues that must be investigated. Firstly the development costs could be quite high if a demonstration mission is required; on the other hand the demonstration of the upper stage and Vinci engine is already in the Ariane 5 evolution plan. Secondly, it has to be investigated whether this is feasible in the schedule constraints that are imposed by the ISS lifetime. Even if the thrust level is quite high, the maximum acceleration brought upon the station is of 0.45 m/s^2, this should not pose any concern on the structural level, but a deeper investigation is recommended to evaluate the structural response of the ISS.

6. CONCLUSION

The ISS uncontrolled impact represents hazard of high probability (10^{-2}) and high consequences (several casualties).
Therefore an active de-orbit scenario should be selected. From the presented list in chapter 5, the most convincing ones are scenario II: natural decay plus ATV and the scenario VI: ESC-B with ATV docking system.
The scenario II is feasible with the today technologies even if the associated risk is still quite high. The scenario IV presents the lowest associated risk at the price of the design of a new vehicle based on not yet proved technologies.
Table 1 summarizes the scenarios with an indication of the risk, complexity and cost associated to each of them. The most promising scenarios are highlighted in bold.
This paper contains just a preliminary analysis and should be used as starting point for a critical review of the possible scenarios in order to perform the de-orbit of the ISS with the lowest acceptable level of risk.

Table 1. Scenario summary

Scenario	*Risk*	*Complexity*	*Cost*
I. Uncontrolled	Very High	Low	Low
II. Drag + controlled	**High**	**Medium**	**Medium**
III. Fully controlled	Medium	High	High
IV. Controlled of several parts	Medium	Very High	High
V. Recycling	Low	Very high	Very High
VI. New vehicle	**Low**	**Medium**	**High**

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