IAC-23-A6.4.7

On the Need to Assess and Mitigate the Risk from Uncontrolled Re-entries of Artificial Space Objects in View of the Current and Future Developments in Space Activities

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Abstract

From 1 January 2010 to 24 August 2023, 566 orbital stages and 511 spacecraft with a radar cross section > 1 m^2 have re-entered without control the Earth's atmosphere. The total returned mass was 1650 metric tons, corresponding to a mean of 115 metric tons per year. 77% of the mass belonged to orbital stages, 23% to spacecraft. The uncontrolled re-entries of orbital stages are currently dominated by China, accounting for more than half of the decaying mass, while for spacecraft 2/3 of the mass belongs to American satellites. 60% of the re-entries occurred within 2 years of the launch. The ground casualty expectancy due to orbital stages was always predominant over that from spacecraft, by an average factor of nearly three. From 2010 to 2018, the total casualty probability remained substantially stable, with a mean annual value just over 1%. Since 2019, instead, the annual casualty probability of both spacecraft and orbital stages progressively increased, reaching a total value of around 3% in 2022 and 2023 (extrapolated). Even assuming a stable launch activity, in the coming years, when many of the recently launched spacecraft will start to re-enter, the casualty expectancy of orbital stages will remain basically the same, while that of spacecraft might progressively increase by a factor of 20. This would lead to an annual casualty probability of about 20%, even more in case of a further growth in launch activity, very likely based on current forecasts. The quick implementation of widespread and effective mitigation measures, like controlled de-orbiting and design for demise, is therefore necessary, to prevent the situation from deteriorating too much.

Keywords: Uncontrolled re-entries, re-entry risk, casualty expectancy, casualty probability, orbital stages, spacecraft.

1. Introduction

Since 2005, when a 44-year low (52) was hit, orbital launches have progressively increased again, stimulated by private actors, new space powers (China and India), emerging countries, and the transition to multi-object payloads and large satellite constellations. Since 2021, all records from the 1960s, 1970s and 1980s have been broken and the number of operational satellites is expected to increase tenfold over the next decade. This sustained level of space activity, even if constrained at the current level (~200 orbital launches and ~2000 satellites per year), will lead to a considerable increase of the probability of destructive collisions in orbit, but will also increment the risk on the Earth due to uncontrolled re-entering space objects, both spacecraft and orbital stages.

An example of the latter are the numerous Chinese orbital stages re-entered without control, in particular since 2016. Four of them, with a mass around 20 metric tons each, decayed between May 2020 and November 2022. Six, with a mass of about 6 metric tons, re-entered between July 2016 and May 2023, while 14, with a mass around 5 metric tons, plunged into the Earth's atmosphere between October 2011 and June 2023. Fragments, believed to belong to several of these stages, were recovered on the ground. The latest findings were a 5 meters in diameter charred metal ring, found in Kalimantan, Indonesia, and a piece of metal found near two houses in Sarawak, Malaysia. Both fragments belonged to the big first stage of the Long March 5B rocket used to launch the second module, named Wentian, of the Chinese space station Tiangong.

The re-entry of fragments from decaying orbital objects has fortunately not caused any casualties so far. In 2022, the estimated global annual casualty probability associated with the uncontrolled re-entry of large (i.e. having a radar-cross-section > 1 m^2) orbital stages and spacecraft was 2.8%. For orbital stages, the annual casualty probability was 2%, while for spacecraft it was 0.8%. Therefore, even if the present risk from uncontrolled re-entries is still relatively small, compared with all other hazards faced in everyday life, such risk was found to slightly grow during the last five years, and it may still increase substantially in the near future, due to the current trends in space activities.

Following up on the analyses carried out by the authors over the past decade [1-4], the statistics and ground casualty risk of uncontrolled re-entries of large spacecraft and orbital stages were revisited, updated and extended in this paper, by covering the period from the beginning of January 2010 to 24 August 2023 (13.6 years). The re-entries were characterized in terms of number, mass and estimated casualty risk on ground, also including the country of origin of the decaying objects.

The revised analysis was carried out to assess how the re-entry risk has evolved since 2010, when the so-called "new space economy" was still to come, and to estimate how this risk might evolve in the near future, marked by a level of space activity never seen before. Recommendations drawn from the results presented will then conclude the paper.

2. Uncontrolled re-entries: numbers and masses

In this paper the attention was focused on the spacecraft and orbital stages classified as "large" (i.e. with a radar cross section > 1 m^2) by the 18^{th} US Space Control Squadron. From 1 January 2010 to 24 August 2023, 566 orbital stages and 511 spacecraft (1077 in total) have re-entered without control the Earth's atmosphere.* The total returned mass was 1650 metric tons, corresponding to the re-entry of 115 metric tons per year, on average.† 77% of this mass belonged to orbital stages, with an annual average of 89 metric tons, while the remaining 23% to spacecraft, with an annual average of 26 metric tons.

Figure 1 shows the annual number of uncontrolled re-entries of large spacecraft and orbital stages, while Figure 2 shows the corresponding masses. The main feature of Figure 1 is the significant increase of the number of uncontrolled re-entries of large spacecraft observed since 2018. The mean annual increase, by almost 7 times, was mainly due to constellation satellites, typically smaller and lighter than the average "large" spacecraft of the pre-megaconstellation era, so the corresponding mean annual growth of the re-entering mass was limited to 45%, that is to about 10 metric tons per year.

The uncontrolled re-entries of orbital stages, on the other hand, did not increase very much in numerical terms (less than 30% as annual average), also for the widespread adoption of controlled de-orbiting, in particular by the Falcon 9 second stage, but the corresponding mass re-entering uncontrolled each year grew by an average of 46%, that is 35 metric tons, since 2018 (Figure 2), due to the increasing number of orbital launches and to the growing fraction of massive Chinese rocket bodies (see Section 3).

In summary, from 2010 to 2017, large orbital stages re-entered uncontrolled three times more often than large spacecraft, but since 2018 the situation has reversed, with the uncontrolled re-entries of large spacecraft prevailing by 55%. However, concerning the corresponding re-entering mass, the dominance of large orbital stages was unaffected since 2010, steadily prevailing by more than three times over large spacecraft.

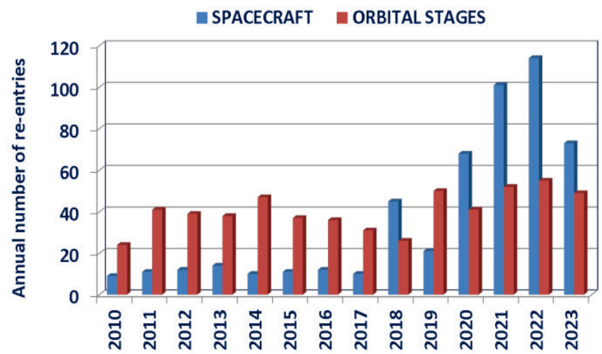

Fig. 1. Annual number of uncontrolled re-entries of large spacecraft and orbital stages, from 1 January 2010 to 24 August 2023.

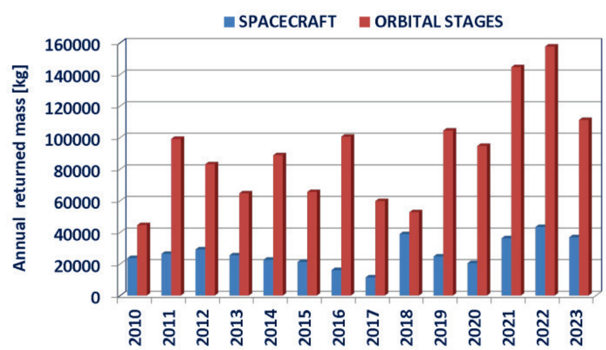

Fig. 2. Large spacecraft and orbital stages mass (kg) re-entered uncontrolled from 1 January 2010 to 24 August 2023.

3. Uncontrolled re-entries per country

Of course, not all countries contribute to the problem in the same way and, as might have been expected, it is the major space powers that have the greatest impact.

3.1 Uncontrolled re-entries of large orbital stages

Starting from the largest source of uncontrolled re-entry mass, i.e. orbital stages, the scene is dominated by just three players, accounting for about 90% of the total number (Figures 3 and 4) and mass (Figures 5 and 6): China (PRC), the countries of the former Soviet Union (CIS) – mainly Russia and, to a lesser extent, Ukraine – and the United States (US). India (IND), France (FR) and Japan (JPN) account for another 9%, while Iran (IRAN), the European Space Agency (ESA), Israel (ISRA) and North Korea (NKOR) contribute to the remaining 1%.

Focusing the attention on the key players, Figure 7 shows how the number of uncontrolled re-entries of large orbital stages evolved since 2010, while Figure 8

* These numbers were estimated using the database of the US Space-Tack organization at https://www.space-track.org.

† The main source of mass data was the ESA's DISCOS database at https://discosweb.esoc.esa.int/.

does the same for the mass. Both plots highlight China's rapid rise, the slow decline of Russia (CIS) and the slight increase of the US contribution. Since 2019, China has largely prevailed in the uncontrolled re-entry of large orbital stages, crossing the threshold of 100 metric tons in 2022. Chinese rocket bodies accounted for 42% of the mass of orbital stages re-entered uncontrolled during the period considered, from 1 January 2010 to 24 August 2023, followed by CIS (34%), by the US (15%), and by India, France and Japan (3% each), as shown in Figures 6 and 9.

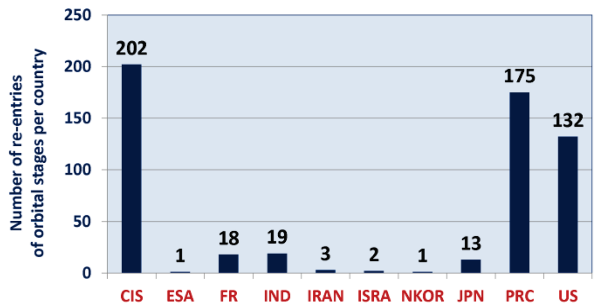

Fig. 3. Number of uncontrolled re-entries of large orbital stages per country, from 1 January 2010 to 24 August 2023.

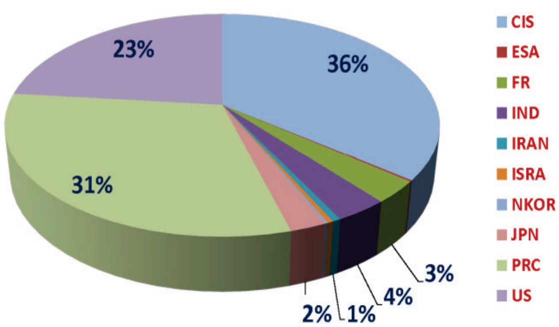

Fig. 4. Fractional contribution – by country – to the number of uncontrolled re-entries of large orbital stages, from 1 January 2010 to 24 August 2023.

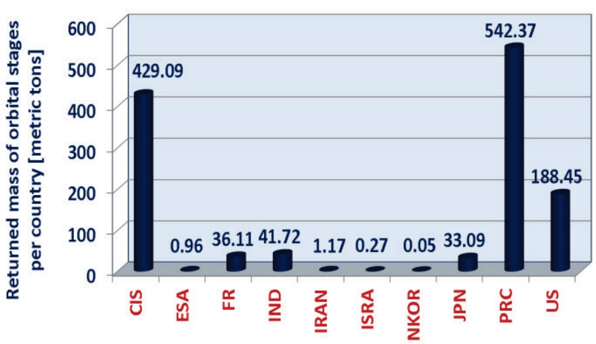

Fig. 5. Returned mass (metric tons) per country, associated with large orbital stages, from 1 January 2010 to 24 August 2023.

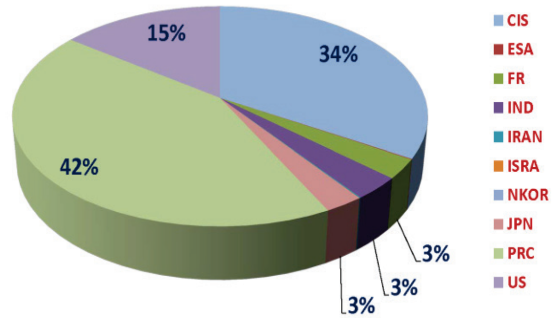

Fig. 6. Fractional contribution – by country – to the mass of uncontrolled re-entries of large orbital stages, from 1 January 2010 to 24 August 2023.

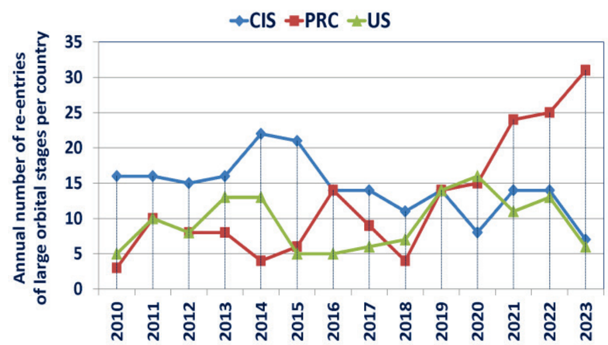

Fig. 7. Annual number of uncontrolled re-entries of large orbital stages due to the three main players, from 1 January 2010 to 24 August 2023.

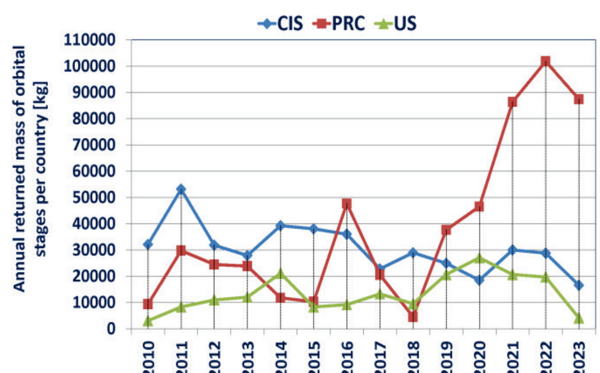

Fig. 8. Mass (kg) of large orbital stages re-entered uncontrolled from 1 January 2010 to 24 August 2023, due to the three main players.

Narrowing the focus to what has happened from 2018 onward, the Chinese percentage has grown to 55%, followed by CIS (22% and declining), the US (15% and stable), India (5%), Japan (2%) and France (1%), as shown in Figure 10. No re-entry of ESA's and Iran's orbital stages was recorded in this time frame, while one light orbital stage re-entered both for Israel (170 kg) and North Korea (50 kg).

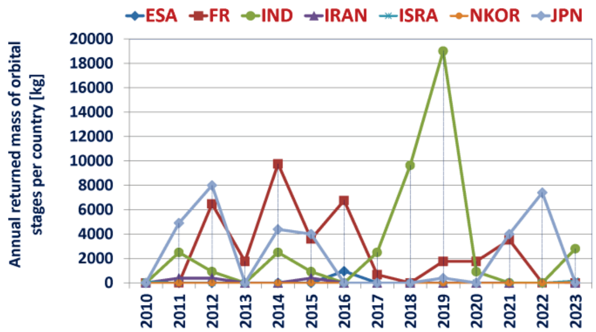

Fig. 9. Mass (kg) of large orbital stages re-entered uncontrolled from 1 January 2010 to 24 August 2023, due to the rest of the world.

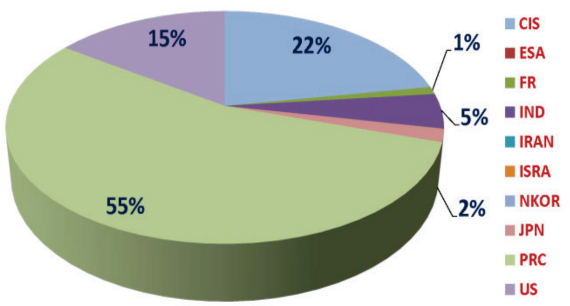

Fig. 10. Fractional contribution – by country – to the mass of uncontrolled re-entries of large orbital stages, from 1 January 2018 to 24 August 2023.

3.2 Uncontrolled re-entries of large spacecraft

Switching the attention to large spacecraft re-entering without control, again the scene is dominated by just three players, accounting for about 95% of the total number (Figures 11 and 12) and mass (Figures 13 and 14), that is the United States, CIS and China. The remaining 5% is instead associated with spacecraft from Japan (JPN), India (IND), Germany (GER), European Space Agency (ESA), Indonesia (INDO), South Africa (SAFR), Taiwan (TWN), New Zealand (NZ) and Argentina (ARGN), in order of decreasing returned mass.

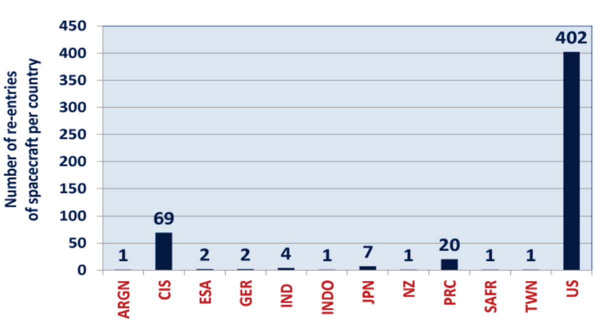

Fig. 11. Number of uncontrolled re-entries of large spacecraft per country, from 1 January 2010 to 24 August 2023.

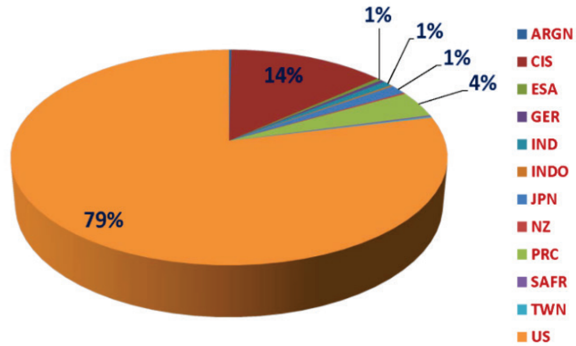

Fig. 12. Fractional contribution – by country – to the number of uncontrolled re-entries of large spacecraft, from 1 January 2010 to 24 August 2023.

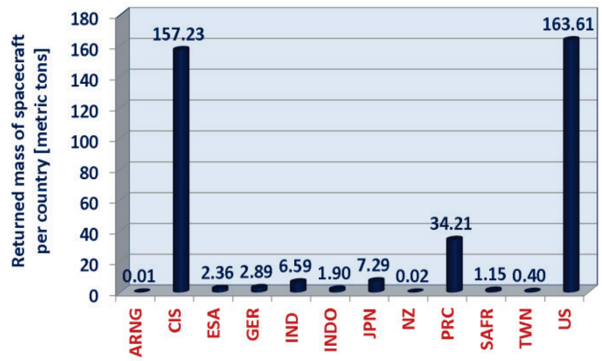

Fig. 13. Returned mass (metric tons) per country, associated with large spacecraft, from 1 January 2010 to 24 August 2023

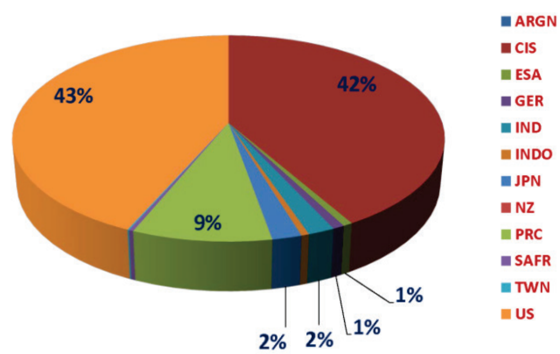

Fig. 14. Fractional contribution – by country – to the mass of uncontrolled re-entries of large spacecraft, from 1 January 2010 to 24 August 2023.

Figure 15 shows how the number of uncontrolled re-entries of large spacecraft, from the three main players (US, CIS and PRC), evolved since 2010, while Figure 16 does the same for the mass. Both plots highlight the sudden rise of re-entries of US spacecraft, linked to the operation of satellite constellations and dominating all other number and mass contributions since 2018. Regarding the numbers, those of CIS and China remained roughly stable during the period considered, while for the mass it was again roughly stable for China and declining for CIS.

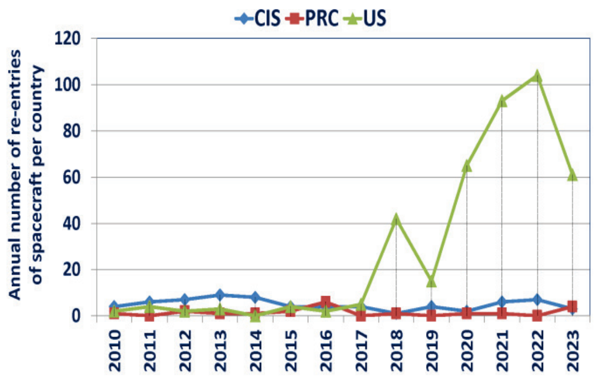

Fig. 15. Annual number of uncontrolled re-entries of large spacecraft due to the three main players, from 1 January 2010 to 24 August 2023.

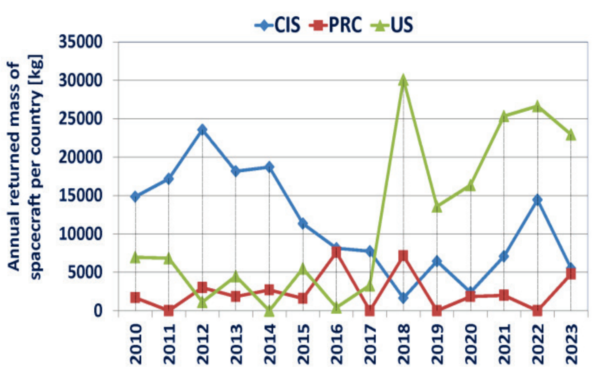

Fig. 16. Large spacecraft mass (kg) re-entered uncontrolled from 1 January 2010 to 24 August 2023, due to the three main players.

From the beginning of 2010 to the first eight months of 2023, the large American satellites accounted for 43% of the spacecraft mass re-entered uncontrolled, nearly matched by the CIS satellites with 42%. Well behind China in third place, with 9%. However, considering what has occurred since 2018, the American percentage has grown to 67%, that of CIS has decreased to 19%, that of China has remained basically stable at 8%, while India has attained 3% (Figure 17).

3.3 Synopsis on uncontrolled re-entries of large intact objects

In summary, the uncontrolled re-entries of large orbital stages are currently dominated by China, accounting for more than half of the decaying mass, while for large spacecraft 2/3 of the mass belongs to American satellites.

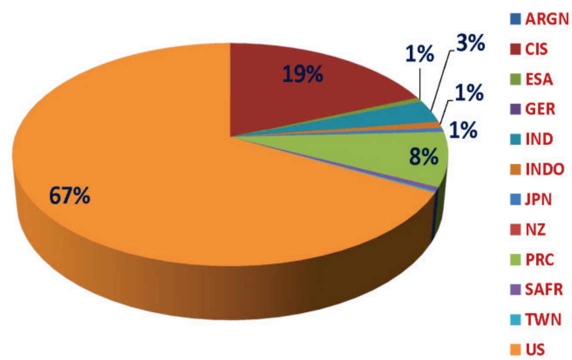

Fig. 17. Fractional contribution – by country – to the mass of uncontrolled re-entries of large spacecraft, from 1 January 2018 to 24 August 2023.

4. Distribution of uncontrolled re-entries in terms of the launch elapsed time

Once the launch has occurred, after how long does uncontrolled re-entry occur?

4.1 Large orbital stages

Figure 18 provides the answer for large orbital stages. As expected for upper stages, that typically conclude their mission within a few hours after the launch, the number of re-entries decreases with increasing orbital lifetime, which is basically driven by the final orbit reached after payload deployment.

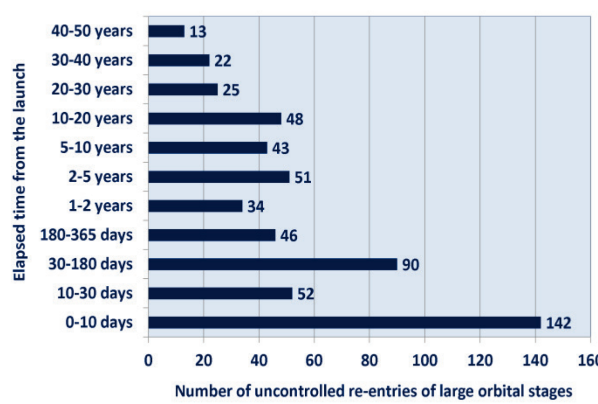

Fig. 18. Large orbital stages: distribution of uncontrolled re-entries as a function of the launch elapsed time (from 1 January 2010 to 24 August 2023).

During the period considered, half of the re-entries (284) occurred within 180 days of the launch, 34% (194) in the first 30 days, and 25% (142) in the first 10 days. Most of the latter (98, or 69%) were Russian Soyuz second stages, but all the four Chinese CZ-5B massive first stages orbited so far were included as well, together with other 13 Chinese, 7 Russian and 20 American rocket bodies. It is also worth mentioning that 96 stages decayed within 3 days, and 49 within 2 days, offering not much time to set up accurate re-entry prediction campaigns. Among these rapidly decaying orbital stages, the clear majority were Russian Soyuz second stages, being 96% of those re-entering within 72 hours and 78% of those re-entering within 48 hours.

4.2 Large spacecraft

Regarding large spacecraft (Figure 19), the situation is of course quite different, because the orbital lifetime is driven by mission duration and critical failure rate. Over the period considered, the orbital lifetime of the re-entered spacecraft had a peak between one and two years. 230 spacecraft (45%) had a lifetime longer than two years, 138 (27%) shorter than one year, 76 (15%) shorter than 180 days, 30 (6%) shorter than 30 days, and only 10 (2%) shorter than 10 days. Therefore, for uncontrolled spacecraft, more than enough time is typically available to set up a re-entry prediction campaign, which is important, since re-entry modeling and forecasts for spacecraft are generally more complicated than those for orbital stages, the latter being simpler in geometry and mass distribution.

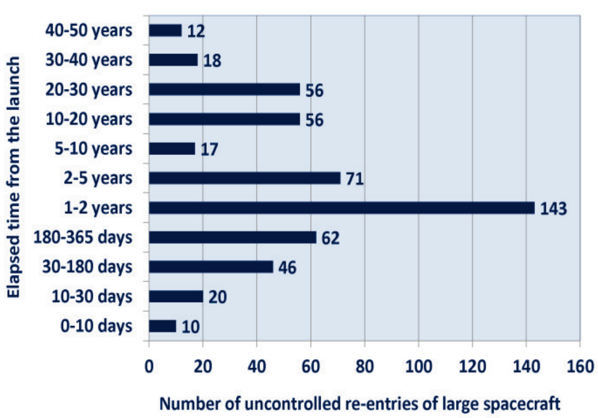

Fig. 19. Large spacecraft: distribution of uncontrolled re-entries as a function of the launch elapsed time (from 1 January 2010 to 24 August 2023).

5. Evaluation of the casualty risk

In order to update the evaluation of the casualty risk on the ground due to the uncontrolled re-entry of large spacecraft and orbital stages, the concepts, the approach and the formulae presented in references [3] and [4] were applied to the revised data set, from 1 January 2010 to 24 August 2023. Figures 20 and 21 summarize the results obtained for the casualty expectancy and probability, respectively.

Throughout the period considered, the risk due to large orbital stages was always predominant over that from spacecraft, by an average factor of nearly three. However, from 2010 to 2018, the total casualty risk remained substantially stable, with a mean annual casualty probability which was just over 1%. Since 2019 the situation has changed, due to the acceleration of new space activities. The casualty expectancies of both spacecraft and orbital stages progressively increased, resulting in a mean annual casualty probability around 3% in 2022 and 2023 (extrapolated). This means that the global re-entry risk has essentially tripled over the past five years, despite the increasing use of controlled de-orbiting for upper stages and massive spacecraft. In other words, the great growth of space activities recently occurred has more than offset, so far, all the efforts put in place to mitigate the problem.

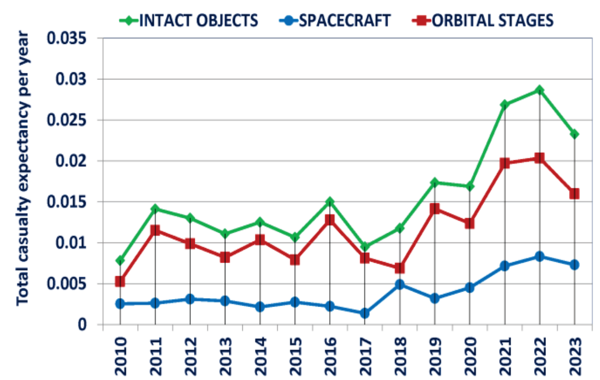

Fig. 20. Annual global casualty expectancy associated with the uncontrolled re-entry of large spacecraft, orbital stages or both (intact objects), from 1 January 2010 to 24 August 2023.

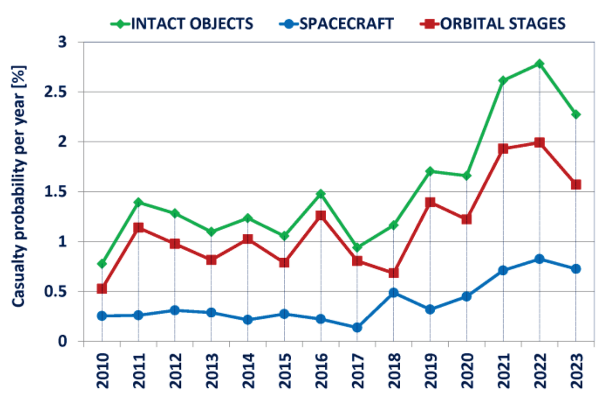

Fig. 21. Annual global casualty probability associated with the uncontrolled re-entry of large spacecraft, orbital stages or both (intact objects), from 1 January 2010 to 24 August 2023.

But not all countries contribute to the re-entry risk in the same way. Again, as expected from the results presented in Section 3, the main contributors are China, CIS (basically Russia) and the Unites States, accounting for 92% of the casualty expectancy due to large orbital stages and 95% of the casualty expectancy due to large spacecraft, during the whole time interval considered.

5.1 Risk due to large orbital stages by country

The evolution, per country of origin, of the casualty expectancy due to large orbital stages is shown in Figure 22. At the beginning of the 2010s, Russian upper stages were the leading contributors, but over the following 12 years their impact slowly declined. Concerning the American rocket bodies re-entering uncontrolled, the associated casualty expectancy slowly increased over the period analyzed, but only in 2020 exceeded that of the Russian stages. China, instead, has become the largely dominant contributor in recent years, more than three times as much as Russia or the United States. Regarding other countries, only India, France and Japan have occasionally given not negligible contributions.

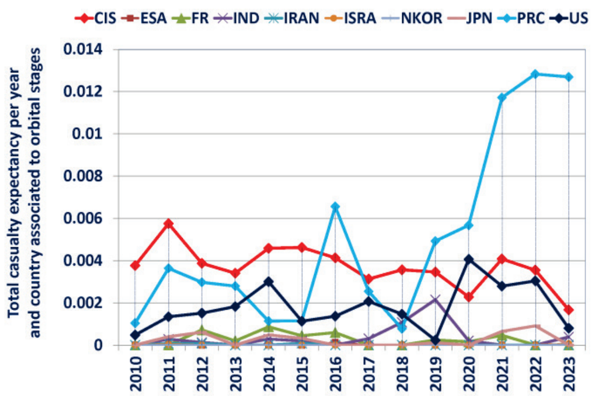

Fig. 22. Annual global casualty expectancy associated with the uncontrolled re-entry of large orbital stages, by country of origin (from 1 January 2010 to 24 August 2023).

5.2 Risk due to large spacecraft by country

The evolution, per country of origin, of the casualty expectancy due to large spacecraft is shown in Figure 23. Even in this case Russia was the leading contributor at the beginning of the 2010s, and again this contribution slowly decreased over the period considered. Since 2018, the dominant player has become the United States, due to the huge numbers of satellites launched and the corresponding increase of uncontrolled re-entries. China, despite being in the third position, has so far only episodically contributed to significant casualty expectancies, followed, still much further behind, by Japan and India.

5.3 Overall risk due to large intact objects

In summary, there is currently (2022-2023) an annual probability around 3% that a fragment of an intact object re-entering the atmosphere uncontrolled will strike someone on the surface of the Earth. 70% of the casualty expectancy is associated with the uncontrolled re-entries of orbital stages, 30% with the re-entries of satellites. Concerning the current (2022-2023) contribution by country of origin of the re-entering objects, China accounts for 51% of the overall re-entry risk, followed by the United States (30%) and by Russia (14%). Considering, instead, the period 2010-2023, China accounted for 35% of the total casualty expectancy, followed by Russia (31%) and by the United States (26%).

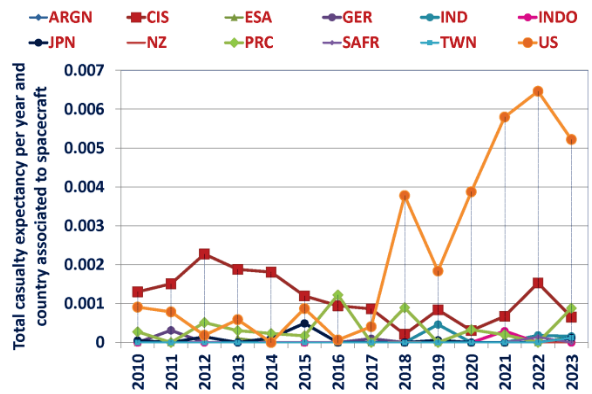

Fig. 23. Annual global casualty expectancy associated with the uncontrolled re-entry of large spacecraft, by country of origin (from 1 January 2010 to 24 August 2023).

6. Evolution of the risk in the near future

Assuming for the near future the current level of space activity, with around 200 launches and 2000 new satellites per year, the expected risk from uncontrolled re-entries may be estimated under the assumption that no further mitigation measures are taken. Today, the casualty expectancy from re-entering spacecraft is less than half of that from uncontrolled orbital stages. In the coming years, however, when many of the recently launched spacecraft will start to re-enter, the casualty expectancy of upper stages will remain basically stable, of the order of 0.02-0.03 per year, while that of satellites might progressively increase by a factor of 20, to 0.20 per year. This would lead to an annual casualty probability of about 20%.

Such unfavorable outcome might be avoided requiring the generalized adoption of controlled de-orbiting for orbital stages and satellites. For the former, in particular those belonging to the most recent rockets, controlled re-entries are already frequently adopted, and it is hoped that the new launchers under development will increasingly implement this requirement. However, for several old launchers still in use today, especially by China and Russia, a controlled de-orbiting will probably not be feasible, so an annual casualty expectancy of 0.01-0.02 due to orbital stages cannot be eliminated quickly.

Concerning the satellites, we are talking about of completely new systems, with design, development and deployment times short enough to implement various appropriate solutions, as controlled re-entry, design for demise and, in certain cases, active removal by a chaser spacecraft. Presently, it is not possible to accurately predict how much successfully the uncontrolled re-entries of new spacecraft will be avoided. There are, for instance, many claims of the adoption of design for demise, but with the information available such claims can neither be confirmed nor quantified in terms of effectiveness. It is therefore unclear by how much the growth in casualty expectancy due to uncontrolled spacecraft re-entry will be kept in check. Also because, in the next decade, even many more satellites than 2000 per year could be launched, further complicating the problem [3].

7. Conclusions and recommendations

Since 2018, large spacecraft are re-entering without control more often than large orbital stages, but the latter are still prevailing on the former in terms of mass by more than three times. Currently, the associated global casualty probability is around 3% per year, 70% of which is due to orbital stages and 30% to spacecraft.

However, the situation is changing fast. In the coming years, in fact, while the casualty expectancy of upper stages might remain basically stable, that of satellites might progressively increase by a factor of 20, just maintaining the current level of space activity. This could lead to an annual casualty probability of about 20%, a value that many would consider too high and unacceptable. And a further increase in space launches, very likely based on current projections, would only exacerbate the problem even more [3].

It is therefore necessary to take effective mitigation measures as soon as possible, for instance requiring the generalized adoption of controlled de-orbiting for large orbital stages and satellites. For the latter, a promising possibility may also be represented by the development and widespread use of effective design for demise components, thereby significantly reducing the mass capable of surviving re-entry. Already today there are, for instance, many claims of the adoption of these technologies, but such claims can neither be confirmed nor quantified in terms of actual achievements.

In any case, to attain significant results under the current conditions, the problem must be addressed now, while new launchers and large constellations of low-orbit satellites are being developed and deployed, otherwise the situation is likely to spiral out of control within a decade.

Acknowledgements

The work described in this paper was carried out in the framework of the research project "Safety and Sustainability of Space Activities", funded by CNR-ISTI (No. DIT.AD012.151). The authors would also like to thank the US Space Track Organization for the catalog of unclassified space objects, and the European Space Agency for the DISCOS database.

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