ATmospheric Impact of SPAcecraft Demise (ATISPADE)

EXECUTIVE SUMMARY
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1. INTRODUCTION

1.1. CONTEXT

The demise of space debris (e.g. upper stages, satellites, their components) re-entering the atmosphere results in emissions into the atmosphere. Typically, most of the re-entering object mass does not survive the atmospheric transit and ends up being released into the atmosphere under gaseous or particulate forms. Depending on the nature and material composition of re-entry debris, a wide range of re-entry gases and particles are released. Some are chemically active, in particular ozone destroying, or/and radiatively active (i.e. climate forcers). For these reasons, there are concerns about the potential impact of re-entry events on stratospheric ozone and climate**.**

In the framework of its Sustainable Development programme, ESA is striving to assess precisely and reliably the environmental impacts of its activities. **The ATISPADE project aims to produce a state-of-the-art assessment on the atmospheric impact of spacecraft demise.** The specific objectives are the following:

- To assess the impact of spacecraft demise on Earth's atmosphere in terms of short term and long-term effects.
- To understand the long-term impact of spacecraft demise of ozone depletion and global warming.
- To quantify the level of toxic elements released into the atmosphere and to assess the hazard potential.

The two main issues covered here are stratospheric ozone depletion and climate forcing. Because of concern regarding surface pollution and toxicity, a smaller component of the project is devoted to deposition at the surface of toxic elements. The focus is on changes in atmospheric chemical composition because the environmental impacts assessed here represent either changes in chemical composition (stratospheric ozone) or are driven by changes in chemical composition of the atmosphere (climate change, toxic deposition at the Earth's surface). It is worth stressing that the potential atmospheric impact of spacecraft demise has been barely touched in the open literature.

1.2. CONTENT

The entire chain of events, from space vehicle re-entry to global atmospheric impact, requires to consider multiple physical, chemical and radiative processes that operate and interact over specific scales, ranging spatially from the scales of spacecraft fragments to atmospheric global scales. The chain can be decomposed in 3 phases. The first phase is **the space vehicles break up, burning and ultimately demise during re-entry** and the resulting gaseous and particulate emissions. It is the domain of aerothermodynamics. The second phase covers the formation and physicochemical processing of re-entry emission plumes, and their **short-term**

impacts on atmospheric composition, notably ozone, at regional scales. The third and final phase covers the transport and chemistry of re-entry emissions throughout the entire atmosphere and their **cumulative long-term impacts on global atmospheric chemical composition (e.g. ozone depletion) and ultimately on climate (radiative forcing)**.

The main findings concern material assessment and re-entry products of representative spacecraft and a representative upper stage, the regional short-term atmospheric impact caused by a large spacecraft re-entry and global long-term impact resulting from the cumulative effect of a decade of re-entries.

1.3. MODEL SYSTEM DEVELOPMENTS

Generally, the two key sources of information on atmospheric impacts are observations and model simulations. **The present assessment is primarily based on state-of-the-art numerical model simulations because observational data on atmospheric impacts (i.e. ozone, climate) of re-entry events appear to be almost non-existent.**

A unique integrated multi-scale multi-model system has been developed in order to simulate all the phases, from the aerothermodynamics of destructive re-entry (including mass loss demise, shock layer and hot wake chemistry), emissions of re-entry products, their atmospheric physicochemical processing and global dispersion, and finally atmospheric removal.

2. MATERIAL ASSESSMENT, RE-ENTRY PRODUCTS AND FREQUENCY SCENARIOS

2.1. ATISPADE AEROTHERMODYNAMICS: RE-ENTRY PRODUCTS

Based on space vehicle composition provided by ESA, representative spacecraft and a representative upper stage have been constructed paying **great attention to materials whose ablation products could potentially be ozone-destroying, climate forcing or/and toxic**. Sets of ballistic coefficient objects and of trajectories are considered in the re-entry destructive model calculations in order to capture the basic behaviour of space vehicle components during re-entry. Organic chemistry has been simulated in both a closed system and an open system, in order to provide a mass loss of the species along the trajectory, as well as an equilibrium chemical composition at the surface of the demising object. The aerothermodynamics calculations have been **refined by the use of CFD simulations which account for the relaxation of the chemistry towards a lower temperature equilibrium state in the hot wake, and allow for the production of nitrogen oxides in the shock layer**. Indeed, the air chemistry products are shown to provide a significant fraction of the generated species of interest.

A summary of the total mass emission of the species re-entry cases as fraction of original space vehicle mass is given in the Table 1 below for 8 different cases (spacecraft/upper stage, controlled/uncontrolled, best guess/worse case):

Table 1: Summary of re-entry products emissions masses expressed as fractions of original space vehicle mass for 8 different cases (spacecraft/upper stage, controlled/uncontrolled, best guess/worse case)

	Uncontrolled				Controlled			
	Spacecraft		Upper Stage		Spacecraft		Upper Stage	
Total Emissions	**Best Guess**	**Worst Case**	**Best Guess**	**Worst Case**	**Best Guess**	**Worst Case**	**Best Guess**	**Worst Case**
Aluminium Particles Mass	0.315	0.346	0.533	0.586	0.237	0.346	0.401	0.586
Titanium Particles Mass	0.008	0.040	0	0	0.028	0.052	0	0
Copper Particles Mass	0.070	0.075	0	0	0.059	0.075	0	0
Steel Particles Mass	0.020	0.060	0.045	0.136	0.013	0.060	0.028	0.135
Glass Particles Mass	0.007	0.062	0.001	0.007	0.032	0.062	0.003	0.007
Carbon Particles Mass	0.004	0.041	0.004	0.029	0.002	0.041	0.003	0.029
Carbon Dioxide Mass	0.091	0.022	0.064	0.015	0.062	0.022	0.044	0.015
Carbon Monoxide Mass	0.018	0.372	0.013	0.259	0.012	0.372	0.00	0.259
Water Mass	0.003	0.011	0.004	0.016	0.003	0.011	0.003	0.016
HCl Mass	0.007	0.008	0.005	0.005	0.007	0.008	0.005	0.005
OH Mass	0.002	0.005	0.001	0.003	0.002	0.005	0.001	0.003
Cl Mass	0.015	0.015	0.010	0.011	0.014	0.015	0.010	0.011
NO Mass	0.350	0.400	0.350	0.400	0.350	0.400	0.350	0.400
O Mass	0.350	0.400	0.350	0.400	0.350	0.400	0.350	0.400
NH3 Mass	0.0005	0.003	0	0	0.0005	0.003	0	0

2.2. EVALUATION OF RE-ENTRY EMISSION COMPOSITION AGAINST ARA AEROTHERMODYNAMIC ASSESSMENT

On this Invitation to Tender (ITT) for 'Atmospheric Impact of Spacecraft Demise', ESA funded two parallel studies, one led by Varuna Ltd (ATISPADE) and the other one led by TAS-I (ARA). The two independent impact assessments were compared towards the end of the projects in order to help to identify and estimate errors in the impact assessments. It is worth stressing that two independent studies on such complex modelling problems are bound to differ very significantly.

Table 2 compares typical emission mass fraction (as fraction of spacecraft mass) for the key ozone-destroying (NO, chlorine) and direct climate forcers (CO_2, H_2O) in ARA and ATISPADE aerothermodynamic assessments.

Table 2: ARA and ATISPADE mass emission (as fraction of spacecraft mass) for key ozone-destroying (NO, chlorine) and direct climate forcers (CO_2, H_2O)

Simulation	ARA	ATISPADE
NO	0.009	0.35
Chlorine	0	0.023
CO_2	0.25	0.09
H_2O	0.07	0.03

The focus is on chlorine and nitrogen oxides NO, the key ozone-destroying species. Per re-entry unit mass, there is about 40 times more NO emitted in the ATISPADE assessment than in ARA. ATISPADE accounts for NO production in the shock layer (which is the main NO source) whereas ARA ignores it. Although there is chlorine in space vehicles, for example in some cyanate ester resin, ARA also ignores chlorine. However, given the very different approaches adopted in the ARA and ATISPADE aerothermodynamics activities and the so many unknowns, the differences are not surprising. Note that large differences in NO and chlorine emissions between ATISPADE and ARA result in large differences in the magnitude of stratospheric ozone losses calculated in the two assessments.

2.3. RE-ENTRY FREQUENCY SCENARIO

Table 3 provide re-entry statistics in frequency (number per year) and mass rate (tons per year) in the ARA scenarios (best-guess (BG) and worse case (WC)), ATISPADE scenarios (Low, and BG/WC), and DISCOS historical data (low and high re-entry period). The important factor for atmospheric impacts is more the re-entry mass than the re-entry number. Overall, the **ARA, ATISPADE and DISCOS re-entry mass rates, the most important parameter for ozone loss, for the worse case scenarios (highly enhanced re-entry periods) are relatively consistent with values ranging between 450 Tons/year (ATISPADE) to 764 Tons/year (ARA) and a value of 550 Tons/year in the DISCOS historical data**.

Table 3: Long-term re-entry frequency (number/year) and re-entry mass rate (Tons/yeart) in ARA scenarios, ATISPADE scenarios and DISCO historical data. The different considered re-entry scenarios are best guess (BG), worst case (WC) or/and low (LW).

Re-entry Dataset	Frequency (number/year)	Mass rate (Tons/year)
ARA	73 (BG) ; 314(WC)	223(BG) ; **764(WC)**
ATISPADE	~40(LW) ; ~500(BG/WC)	~70(LW) ; **~450(BG/WC)**
DISCOS	50 ; 200	100 ; **550**

3. IMPACT OF RE-ENTRY EMISSIONS ON OZONE LAYER AND CLIMATE

3.1. REGIONAL SHORT-TERM IMPACT FROM A LARGE SPACECRAFT RE-ENTRY

- Model-calculated ozone loss **peaks in the lower mesosphere in the first day (<1%) with an ozone column decrease of < 0.005% and a global ozone deficit decrease of < 0.0001% after a week**. Transient regional ozone variations on that scale are probably undetectable and much smaller than ozone natural variability.

- The **overwhelmingly dominant re-entry emissions for short-term ozone losses are nitrogen oxides (NO) and active chlorine radical emissions**. By comparison, all the other re-entry products (CO, H_2O, NH_3, OH, particles) have negligible contributions to ozone destruction. Although heterogenous chemical reactions on the surface of metallic oxide particles can be fast, **re-entry particles are found to be much too big**

to generate surface area-to-mass ratio high enough for driving significant heterogeneous chemistry.

- In terms of global short-term ozone loss, the ATISPADE and ARA (parallel project) models respond in a similar way when forced by emissions from a similar spacecraft re-entry event, suggesting that the differences between **these 2 atmospheric chemistry-climate models are not a significant source of divergence between the ARA and ATISPADE ozone assessments**.

3.2. CUMULATIVE GLOBAL IMPACT OF 10 YEARS OF RE-ENTRY EMISSIONS

- On global scale, accumulation of re-entry emissions leads to a sort of steady-state ozone loss after about 5 years. Ozone is found to be mostly destroyed at high latitudes in the upper stratosphere/mesosphere. For the standard re-entry scenario, **local ozone losses (~0.05%) peak over Antarctica at 40 km**. In terms of total ozone column (vertically integrated local ozone concentration, a key quantity for the amount of UV reaching the surface), **the reduction in Antarctic ozone column reaches ~0.012%** during the austral spring. **Global mean ozone loss (< 0.001%) is found to be negligible**.

- **As found for the short-term impact, the overwhelmingly dominant drivers in the long-term ozone destruction are the emissions of nitrogen oxides and chlorine**. The other re-entry components play a negligible role in long-term ozone destruction.

- The globally averaged **ozone direct climate forcing generated by re-entry perturbations is about -5 (-0.03 to +0.01) µW.m^{-2}**. An extreme upper limit of CO_2 direct forcing generated by 20 years of re-entry is found to be about of the order of the estimated ozone direct forcing. **Both ozone and CO_2 re-entry-generated forcings appear to be totally negligible compared to the ozone indirect forcing generated by CFCs and halons emissions since 1970s or to the CO_2 direct forcing since preindustrial time (+2 W.m^{-2})**.

3.3. EVALUATION AGAINST OTHER MODEL IMPACT ASSESSMENTS: NITROGEN OXIDES AND CHLORINE

- Nitrogen oxides: When the ATISPADE long-term nitrogen-only simulation is compared to ARA long-term model simulations (no chlorine is emitted in ARA), global ozone loss is found to scale approximatively (within 50%) with the amount of nitrogen oxides emissions (see Table 4 below). When accounting for the difference in the amount of nitrogen oxides emitted, **ATISPADE calculations of global ozone losses from re-entry nitrogen oxides are found to be consistent with the results from the parallel study ARA.**

Table 4: Nitrogen oxides re-entry emissions and model-calculated global mean long-term O_3 loss (raw value and per T of NO emissions) for ARA and ATISPADE nitrogen-only simulations

Simulation	NO emissions (Tons/year)	Global mean O_3 loss (%)	Global mean O_3 loss (%) per Ton/yr of NO emissions
ARA best guess	2	0.77E-5	0.38E-5
ARA worse case	6.9	1.7E-5	0.25E-5
ATISPADE NO-only	157	40E-5	0.25E-5

- Chlorine: When the ATISPADE chlorine-only simulation is compared to previous global modelling studies on the long-term impact of solid-fueled (chlorine-rich) rocket emissions on stratospheric ozone, global ozone loss is found to scale approximatively (within a factor 2) with the amount of chlorine emissions (see Table 5 below). When accounting for the difference in the amount of chlorine emitted, **ATISPADE calculations of global ozone losses from re-entry chlorine are found to be consistent with results from previous studies.**

Table 5: Chlorine stratospheric emissions and model-calculated global mean long-term ozone loss (raw value and scaled to 1 T/yr of chlorine emissions) from several studies including ATILA-IC ESA-funded study and ATISPADE Chlorine-only simulation. Ariane 5 corresponds to launches from Kourou and US corresponds mostly to Shuttle launches from Cap Canaveral, Florida.

Study reference	Stratospheric Cl emissions (Tons/year)	Global mean O_3 loss (%)	Global mean O_3 loss (%) per T/yr of Cl emissions
ATILA-IC 3-D model	335 /Ariane 5	0.005 - 0.011[a]	1.5E-5 - 3.3E-5
ATILA-IC 2-D model	335 /Ariane 5	0.0076	2.3E-5
Jackman et al., 1996	725 /US launchers	0.014	1.9E-5
Jackman et al., 1998	725 /US launchers	0.023	3.2E-5
Danilin et al., 2001a	816 /US launchers	0.02	2.5E-5
ATISPADE Chlorine-only	10.3 / Re-entry	30.E-5	2.9E-5

3.4. LONG-TERM CLIMATE FORCING

- The **globally averaged ozone direct climate forcing resulting from re-entry is estimated to be about -5 (-0.03 to +0.01) µW.m^{-2}**. The wide error bars are based on the literature where spectrally coarse radiative models are often used instead of accurate line-by-line radiative models (introducing an error of up to a factor 3) and where the multi-model dispersion on lower stratospheric ozone perturbations (a key altitude range for ozone direct forcing) is very large.

- An extreme upper limit of CO_2 direct climate forcing generated by 20 years of re-entry is found to be about of the order of the estimated ozone direct forcing. By comparison, the other re-entry species generate negligible climate forcing.

- The **climate forcing generated by re-entry appear to be totally negligible compared to the ozone forcing generated indirectly by CFCs and halons emissions since 1970s and to the CO_2 direct forcing since preindustrial time (2 W.m^{-2})**.

4. OUTSTANDING ISSUES

- **Atmospheric observations**: Observational data on the atmospheric impacts of re-entry events are almost non-existent. As a result, the aerothermodynamics and atmospheric model results cannot be evaluated against measurements, notably at plume scales (when perturbations are expected to be extremely large). **In a domain where knowledge is so limited, any model calculations have to be compared to real measurements. The possibility of an atmospheric measurement campaign through a re-entry plume might be explored when a large spacecraft re-entry is planned**.

- **Aerothermodynamics modelling**: On this Invitation to Tender (ITT) for ‘Atmospheric Impact of Spacecraft Demise’, ESA funded two parallel studies, one led by Varuna Ltd (ATISPADE) and the other one led by TAS-I (ARA). The two independent impact assessments were compared towards the end of the projects in order to help to identify errors and estimate uncertainties in the impact assessments. It is worth stressing that two independent studies on such complex modelling problems are bound to differ very significantly.

  As expected, model-calculated ozone losses are very sensitive to the outcome of the aerothermodynamics assessment. The ARA and ATISPADE assessments provide rather conflicting estimations for emissions of chlorine and nitrogen oxides (NO), the overwhelmingly dominant ozone-destroying species. Per re-entry unit mass, there is about 40 times less NO released in the ARA assessment than in the ATISPADE assessment and no chlorine is released in the ARA assessment. The differences are due to differing assumptions. ARA ignores NO production in the high temperature shock layer (which is actually the fundamental source of NO during re-entry). ARA ignores chlorine, though chlorine is known to be present in space vehicles, for example in some cyanate ester resin.

  Since the large differences in NO and chlorine emissions between ATISPADE and ARA result in very large differences in stratospheric ozone losses, it is crucial to constraint better the amount of nitrogen and chlorine that might actually be released into the atmosphere during re-entry. The first step should be to refine the material composition assessment in such a way that the **assumed material composition is as close as possible to the average composition of the re-entry mass and takes into**

account all the materials which are potentially ozone-destroying, climate-forcing, or toxic. There is also the **need to be extremely cautious with some assumptions and simplifications in the aerothermodynamics and favour conservative options**.

- **Atmospheric modelling**: There is a number of improvements required in the global atmospheric modelling. First, the model used here has a resolution of about 200 km in the equator but with a higher resolution at high latitudes. As a result, **small scale processes, notably at the plume scales, were not accounted for. It is unfortunate because ozone losses are expected to be extremely pronounced at local scales**. It is certainly preferable to carry out the atmospheric modelling at higher resolution. For large re-entry events, the **ATISPADE model has the option of zooming with highly enhanced resolution over a given area, allowing better assessment of the short-term impacts of such events**.

  Radiative transfer modelling used for calculating climate forcing is still very uncertain. **Errors can be reduced with the use of accurate line-by-line radiative models and more reliable predictions of lower stratospheric ozone perturbations (a key altitude range for ozone direct climate forcing)**. A higher resolution model would allow a more accurate and reliable simulation of ozone in the lower stratosphere. Note that no other assessments on the atmospheric impacts of re-entry events are available in the literature.