Thermo-mechanical Impact of Thruster Plume Impingement on Space Debris

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Active debris removal (ADR) is defined as a capability to interact with passive orbiting objects, in order to reduce their orbital lifetime [1]. It is known that ADR is necessary to control the unstable growth rate of debris in low Earth orbit (LEO)[2] [3]. Considerable work has been done on assessing the feasibility of active debris removal missions (cite lots here). One proposed method for this is to use plume impingement of a reaction control system (RCS) thruster on the capturing spacecraft. This work looks at the effect of the mechanical and thermal effects of a thruster plume on the debris, in order to assess the risk that this de-tumbling method could cause break-off of material and appendages such as solar panels and antennas. A classification of the severity of different potential debris objects is also presented, in order to quantify this risk of this method, in terms of the likelihood of break-off and the potential impact of the debris.

Nomenclature

(Nomenclature entries should have the units identified)

ρ = density

p = pressure

m = mass

T = Temperature

σ_T = collision cross section

Θ = boundary-layer momentum thickness

Subscripts

E = Nozzle exit flow conditions

$*$ = Throat flow conditions

0 = Stagnation flow conditions

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I. Introduction

Active debris removal (ADR) is defined as a capability to interact with passive orbiting objects, in order to reduce their orbital lifetime [1]. It is known that ADR is necessary to control the unstable growth rate of debris in low Earth orbit (LEO) [2] [3]. Considerable work has been done on assessing the feasibility of active debris removal missions [4, 5]. It showed that during ADR, it is necessary to minimise the spin rate differential between debris and the capturing spacecraft [6]. One proposed method of for this is to use plume impingement of a reaction control system (RCS) thruster on the capturing spacecraft, to create a moment on the debris [7, 8].

A. Plume Impingement

A thruster plume in Earth orbit expands differently to a plume blow the ionosphere, due to the severely low downstream pressure at higher altitudes. Expansion fans at the nozzle exit do not expand according to the Prandtl-Mayer angle, but instead expand more radially as if emanating from a point source at the centre of the nozzle [9]. The low downstream pressure also leads to a decreasing mean free path in the plume- defined as the average distance travelled by a particle between successive particular collisions:

$$\lambda = \frac{m}{\sqrt{2}\rho\sigma_T} \tag{1}$$

As λ increases, the gas transitions from behaving like a continuum where Navier-Stokes (and all derived flow equations) are valid, to a rarefied gas where instead kinetic theory must be applied to accurately capture the particular nature of the gas [10]. The Knudsen number is commonly used to quantify this transition from continuum to rarefaction [11]. This parameter is equal to the mean free path, normalised by a characteristic length. In literature for plume impingement studies, the characteristic length chosen is commonly a nozzle parameter, but can differ between nozzle radius, nozzle diameter, throat radius, and nozzle length [12–15]. Knudsen number is used to split the plume into three regions: continuum region; transition region; and the free molecular region. These regions and the applicable Knudsen number ranges are shown in Figure 1. In the transition region, the gas is neither a continuum or rarefied gas. Often, direct simulation monte carlo (DSMC) computations are used to characterise this region of the flow. In addition, DSMC codes allow for the computation of non-equilibrium thermal balance conditions between a plume and the surface upon which it impinges. Notably, when running DSMC calculations, the distinction between the flow regions from Figure 1 is generally determined by Bird's parameter rather than the Knudsen number. Bird's parameter is simply the Knudsen number where the characteristic length is constrained to the cell size of the mesh [16]. Legge had some success by omitting the transition region, and treating the flow as either continuum or rarefied [17]. Impingement was then calculated in the transition regime by estimating a reduced pressure coefficient: an average of pressure coefficients in the adjacent continuum and free molecular regions. In Legge's case, this averaging was based on experimental data of his specific thruster, and so likely does not constitute a valid general method.

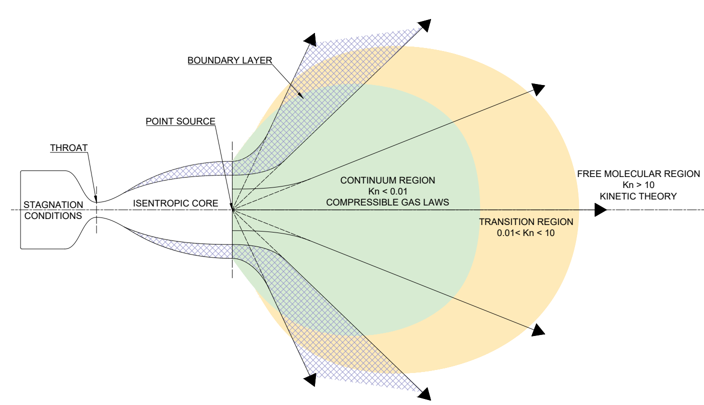

Fig. 1 Flow Regions from an isentropic nozzle exhaust, and their characteristic Knudsen number ranges.

Equation 1 shows for a plume with a single particle species A, and hence a constant particular mass and collision cross section, the mean free path is inversely proportional to the density of the plume. Analytical methods for determining the density field of the plume commonly include Simon's model and Mayer's model [18] [19]. Both of these models estimate the density to decay with axial distance from the nozzle exit, and angle from the centreline. The methods estimate the plume based on the boundary layer thickness of the (assumed isentropic) nozzle flow. Hence, it is critical that the nozzle exit conditions are well defined, ideally by experimental data. It has also been shown that these methods are only valid in the continuum region of the plume [20].

When a plume comes into contact with a surface, it impinges some of the plume energy onto the surface- causing temperature increases and forces on the surface. The impingement of the plume onto a surface is found by imagining a freezing plane. Importantly, analytical models assume that the presence of the surface has no effect on the plume shape and properties; hence the impinged flux and pressure is independent of the freezing surface geometry [21]. From flux and pressure, the temperature of the surface and the force imparted in it can be found from standard equations. Ultimately, it can be determined whether the imparted force will cause failure of the surface at the elevated temperature. Since the impinged surface is debris, and has therefore likely been on-orbit for considerable time, the degradation of the materials due to the space environment (radiation, UV exposure) must also be accounted for when determining the mechanical properties of the surface.

B. Debris Risk from ThermoMechanical Effect

DISCUSSION OF DEBRIS SEVERITY EVALUATION METHODS AND THERMAL AND MECHANICAL 'PROBLEMS' ON THE DEBRIS

The severity of any potential debris created must also be assessed. This severity is most closely associated with the momentum of the debris, and hence the mass. However, the hardness of the debris can also be considered, as a good indicator to the potential sharpness of any debris created. The mass of individual debris object may be considered in larger cases, but in cases of multiple smaller breakages, it is the mass of the debris cloud that must be considered.

I also need to talk hear about the thermal effect of a plume. That is that heat flux can cause melting. Melting of glue between composites, meting of glue for attachments.

This work looks at the mechanical and thermal effects of a thruster plume on the debris, in order to assess the risk that this detumbling method could cause break-off of material and appendages, such as solar panels and antennas. A classification of the severity of different potential debris objects is also presented, in order to quantify the risk of this method in terms of the likelihood of break-off and the potential impact of the debris.

II. Methodology

To assess the risk of debris breakoff, a failure mode and effect analysis (FMEA) was conducted, to identify any failure modes that were of significant concern, and ultimately allowing for the verification of an ADR mission as per the space debris mitigation requirements as outlined by the standard NSASA-STD-8719.14C [22]. An FMEA generates a risk priority number (RPN) for each failure mode, found from the product of severity, occurrence, and detectability. In this way, failure modes could be identified that presented a significant risk to other space systems (severity), and also posed a significant risk of occurring as a result of plume impingement on the source debris.

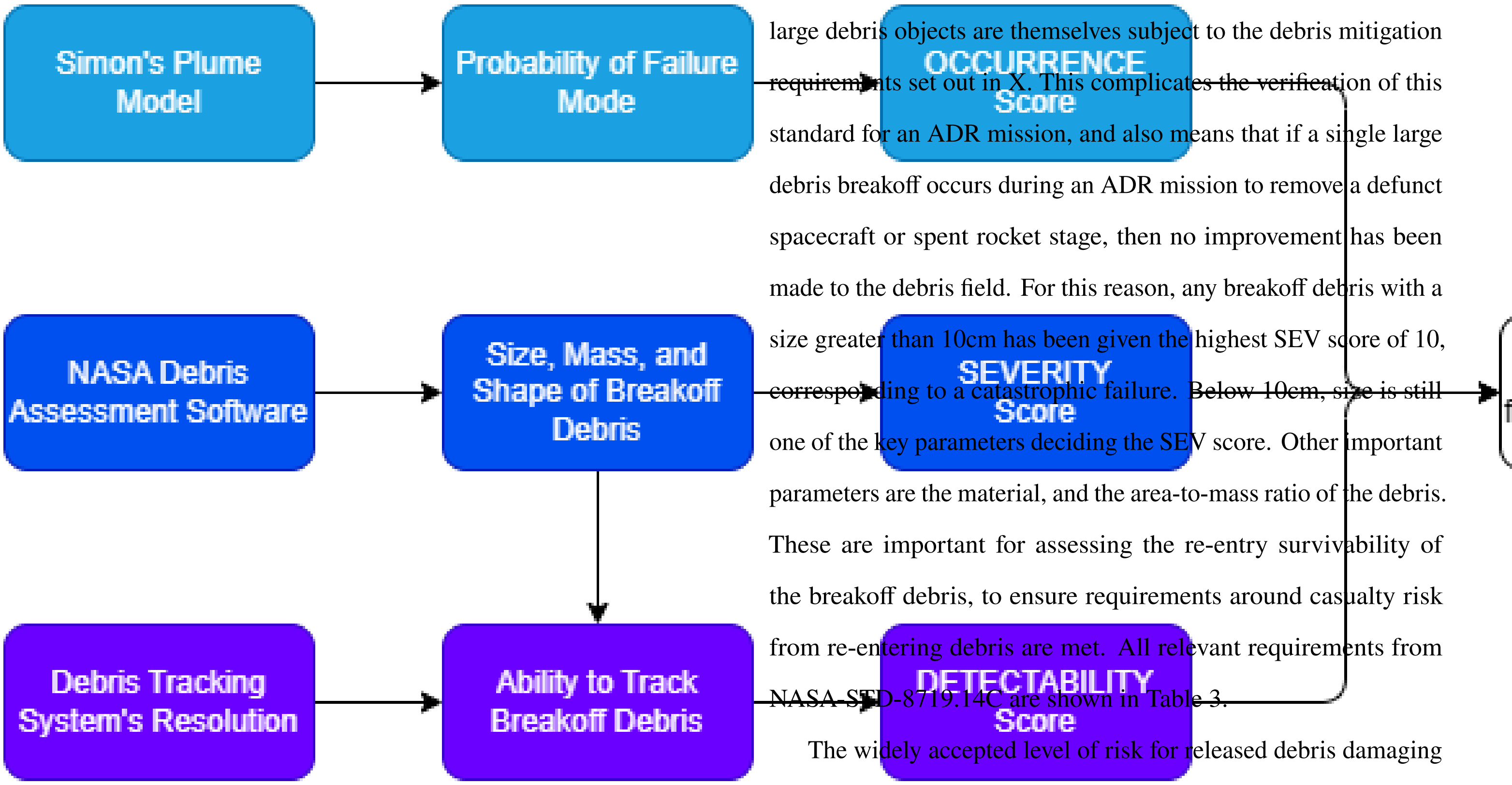

Fig. 2 General workflow presented in this paper to complete a Failure Mode and Effects Analysis from plume impingement.

A. Severity Rubric

The severity (referred to as SEV), of a breakoff debris piece was scored on a rubric shown in Table 2.

The severity score is primarily driven by the size and weigh of the breakoff debris. Both US and European standards define a large debris object to be a debris with a maximum length greater than 10cm. Crucially, large debris objects are viewed the same a in-tact space systems when evaluation collision severity. As a result, large debris objects are themselves subject to the debris mitigation requirements set out in X. This complicates the verification of this standard for an ADR mission, and also means that if a single large debris breakoff occurs during an ADR mission to remove a defunct spacecraft or spent rocket stage, then no improvement has been made to the debris field. For this reason, any breakoff debris with a size greater than 10cm has been given the highest SEV score of 10, corresponding to a catastrophic failure. Below 10cm, size is still one of the key parameters deciding the SEV score. Other important parameters are the material, and the area-to-mass ratio of the debris. These are important for assessing the re-entry survivability of the breakoff debris, to ensure requirements around casualty risk from re-entering debris are met. All relevant requirements from NASA-STD-8719.14C are shown in Table 3.

The widely accepted level of risk for released debris damaging another operational spacecraft is 10^{-6} over the life of the decay. This requirement is what corresponds to the requirement for 100-object years in 4.3-1b. Both 4.3-1a and 4.3-1b are applicable to all debris objects with a maximum length greater than 1mm.

NOTE: this cross sectional area comes from the average cross-sectional area. area-to-mass ratio can then be found from average cross-serctional area / final mass. final mass can simply be taken as spacecraft dry mass in most cases. we assume that any pieces of debris broken off are in non-stabilised attitudes. Hence this is the avaerag cross sectional area for all aspect angles of the debris.

Table 2 Severity scoring rubric used in the FMEA, based of the NASA-STD-8719.14C standard.

Score	Category	Definition	Key Parameters
10	Catastrophic	• Mission failure or destruction of a critical space asset. • Generates large debris clouds, creating cascading collision risks (e.g., Kessler Syndrome).	• Debris size > 10 cm. • High collision probability with operational spacecraft. • Long orbital lifetime (> 25 years).
8–9	Critical	• Major damage to critical systems, causing significant loss of functionality. • May require evasive maneuvers or repairs.	• Debris size 1–10 cm. • High velocity (> 10 km/s) and significant orbital intersection with active spacecraft.
6–7	Serious	• Damage to secondary systems or partial loss of operational capacity. • Increases debris environment risks moderately.	• Debris size 1–10 cm. • Medium collision probability or orbital lifetime (> 10 years but < 25 years).
4–5	Moderate	• Limited damage to a spacecraft or system; no immediate mission impact. • Debris poses localized risk to other objects.	• Debris size 1 mm–1 cm. • Moderate collision probability. • Orbital lifetime < 10 years.
2–3	Minor	• Negligible operational impact; damage restricted to low-priority systems or components. • Debris unlikely to propagate collisions.	• Debris size < 1 mm. • Low collision probability. • Orbital lifetime < 5 years.
1	Insignificant	• No noticeable operational impact; debris likely to re-enter without posing risks.	• Debris size < 1 mm. • Negligible collision probability. • Orbital lifetime < 1 year.

These average cross sectional areas are determied by DAS.

A simplifaication of debris objects considered in this work will be used. All debris shapes used shall be convex shapes, and their average cross-sectional area approximated as 1/4 of the surface area.

The initial orbit of a debris object is taken to be the orbit of the source object. This assumption is valid for debris ejections with a $\Delta V < 10m/s$ different than that of the source object. This sets the practical limit for spin rates considered in this work such that the linear velocity corresponding to the spin trate of the source debris does not lead to a breakoff debris ejection speed greater than 10m/s, from the equation $r\omega = \Delta V < 10m/s$, where r is taken from the centre of rotation for the source debris. In the case of explosive occurences, additional deltaV wil be added to the breakoff debris, that is not considered in this work. For this reason, the DeltaV occuring from the source debris spin rate should be well below 10m/s.

It may be that enough justification simply cannot be made for explosive cases, for their severity to be accurately determined, and for that reason their severity is either rated much higher, or their consideration is ommited entirely.

Can also mention the effect of solar cycle, probably weont

Appendix

An Appendix, if needed, appears **before** research funding information and other acknowledgments.

Table 3 Requirements for Debris Mitigation from NASA standards and ECSS standards.

Req No.	Requirement Text
4.3-1a	All debris released during the deployment, operation, and disposal phases shall be limited to a maximum orbital lifetime of 25 years from date of release.
4.3-1b	The total object-time product shall be less than 100 object-years per launch vehicle upper stage or per spacecraft.
4.4-1	The integrated probability of explosion for all credible failure modes of each spacecraft and launch vehicle is less than 0.001
4.4-2	Either: deplete all onboard sources of stored energy and disconnect all energy generation sources when they are no longer required for mission operations or postmission disposal; or control to a level which cannot cause an explosion or deflagration large enough to release orbital debris or break up the spacecraft.
4.5-1	During the orbital lifetime of each spacecraft and orbital stage, the probability of accidental collision with space objects larger than 10 cm in diameter is less than 0.001.
4.5-2	During the mission of the spacecraft, the probability of accidental collision with orbital debris and meteoroids sufficient to prevent compliance with the applicable postmission disposal maneuver requirements is less than 0.01.
4.6-1a	Using conservative projections for solar activity, atmospheric drag will limit the orbital lifetime to as short as practicable but no more than 25 years after the completion of mission.
4.7-1	The risk of human casualty from surviving debris shall be less than 0.0001

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