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Initial Conditions of a Novel CubeSat during Atmospheric Re-Entry

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Abstract

Despite the establishment of Design for Demise (D4D) as a debris mitigation process, little is still known about the conditions under which debris fragment or survive during re-entry. STRATHcube, a student-led CubeSat project for Space Situational Awareness developed at the University of Strathclyde, aims to contribute to the development of D4D through its secondary payload, providing data on the aerothermal conditions and forces experienced by the satellite during fragmentation upon atmospheric re-entry. The experiment is underpinned by the satellite's stability during re-entry and until fragmentation, which will allow for data to be transmitted in real time.

This paper focusses on the configuration of the solar arrays of the CubeSat and on its attitude during re-entry. Their effect on the operating conditions of the components necessary for recording and transmitting data is explored through a low fidelity model constructed within ESA's Debris Risk Assessment and Mitigation Analysis (DRAMA) tool. Temperature data obtained from this model during the aerothermal demise of the solar panels are also used as a reference point for the design of the thermal protection system. This analysis will advise the requirements of the deorbit manoeuvre of the CubeSat, the alignment of its solar panels for re-entry, and of the thermal protection components necessary for the success of the experiment.

Keywords: STRATHcube mission; CubeSat; atmospheric re-entry, DRAMA

Nomenclature

A_{wet}	*Wetted area*	m^2
H	*Altitude*	*km*
Kn	*Knudsen number*	-
t	*Time*	*s*
T	*Temperature*	*°C*
V_∞	*Velocity of free stream*	*km/s*
α	*Angle of attack*	°
φ	*Configuration angle*	°

Acronyms/Abbreviations

Al	Aluminium
AoA	Angle of Attack
D4D	Design for Demise
DRAMA	Debris Risk Assessment and Mitigation Analysis
LEO	Low Earth Orbit
SA	Solar Array

1. **Introduction**

1.1 Background

The accumulation of debris around Earth, particularly in Low Earth Orbit (LEO), is a recognised concern within the space community, and a result of the amassment of both active and inactive satellites. Without attitude correction, perturbations cause the orbital decay of uncontrolled objects and eventually their demise during atmospheric re-entry. Re-entry analysis tools are used to assess and minimise the risk of satellites disposed of via atmospheric re-entry as part of Design for Demise (D4D) studies. These studies are used to inform the design of a satellite to ensure it poses no significant risk to Earth following re-entry.

The employment of D4D influences the design, configuration, and selection of materials for satellites [1]; thus, the findings of these studies can have costly implications for satellite missions. However, the harshness of the re-entry environment limits the collection of experimental and flight data, introducing significant uncertainty to demise predictions.

1.2 The STRATHcube Mission

As such, the STRATHcube mission was developed by the Strathclyde Aerospace Innovation Society (StrathAIS) at the University of Strathclyde in 2020 with the aim of launching a student-led 2U CubeSat for the sustainable usage of space [2]. STRATHcube has two payloads; the first to track debris in orbit [3] and the second, the subject of this paper, to record the conditions under which the solar panels break away during atmospheric re-entry [4].

The secondary payload, proposed and outlined by Graham et al. [4], relies upon an aerodynamically stable re-entry that will allow the collection and transmission of flight data related to heat and motion history, temperature, and pressure. The experiment is concluded with the fragmentation of the solar arrays (SA) from the main structure, ceasing the provision of aerodynamic stability to the CubeSat and thus breaking the data uplink to the Iridium constellation. Successful transmission would provide the space community with a first-of-its-kind insight into the aerothermodynamic conditions experienced by re-entering objects upon fragmentation. An overview of the stages of the experiment are given in Figure 1.

One of the main challenges of the experiment is the survival of payload-critical components in the harshness of the re-entry environment. Thermal protection systems are not part of the preliminary design, not only due to mass and volume limitations, but also because the mission aims to produce aerothermodynamic data that could be correlated to uncooperating targets such as debris or inactive satellites [4]. Considering that heat flux is a function of exposed surface area across all flow regimes, manipulating the attitude of the satellite during re-entry is a powerful means of reducing the exposed area and minimising the temperature within the CubeSat main structure. Temperature gradient optimisation has the potential of prolonging the lifetime of payload-critical components and enabling the transmission of data to the Iridium constellation.

1.3 Scope of Study

The aim of this study is to investigate the attitude of the satellite during re-entry with respect to prolonging the operational lifetime of its sensor platform and other critical components, thus maximising the output of the fragmentation experiment. The parameters explored are the configuration of solar arrays, and the angle of attack of the satellite during re-entry, as they are the main drivers of the area exposed to the flow. The methodology applied for this study is given in Section 2, with a discussion of the re-entry model used in Section 2.1 and an overview of the resulting limitations and assumptions associated with the study in Section 2.2. The results of this study are collated in Section 3 and considered with a discussion in Section 4.0. The paper concludes with a review of further work and the conclusions in Section 5.0.

2. Re-entry Model

The objective of this analysis is to record the predicted conditions under which the first major fragmentation event occurs. This is due to the experiment terminating upon fragmentation of the solar panels even if components have survived the aerothermal conditions thus far.

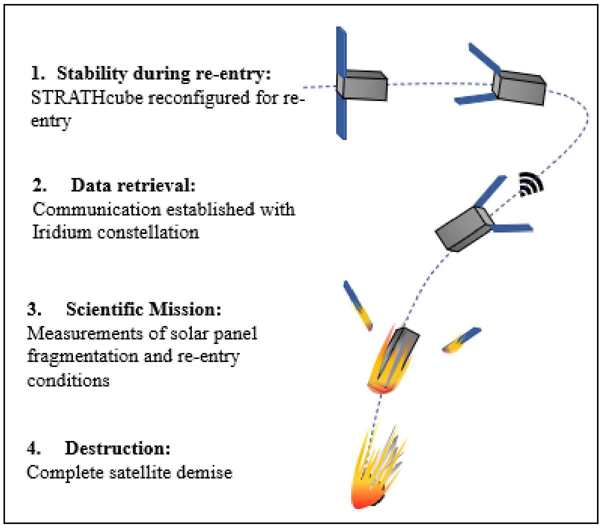

Figure 1: Artistic illustration of the stages of the secondary payload experiment [2]

The analysis uses the European Space Agency's object-oriented re-entry analysis tool DRAMA [5]. Within the DRAMA suite, spacecraft are modelled as a series of connected primitive geometric shapes. As a result, aerothermodynamic parameters related to the atmospheric re-entry are calculated assuming a lumped mass model for each component [6] while thermal analysis is implemented with a 1-D heat conduction model [7]. Nonetheless, his tool allows for the progressive fragmentation of satellites for user-defined dissolution triggers; this is vital for STRATHcube, as this analysis produces a worst-case prediction of maximum temperature within the satellite chassis whilst on an optimal, minimum aerothermal flux trajectory.

This section presents the methodology and underlying assumptions behind the simulations conducted using DRAMA.

2.1 Simulation Setup

The independent variables of this analysis are the configuration of the solar panels, given by angle φ and the angle of attack (AoA) α, and have ranges $90^\circ \leq \varphi \leq 175^\circ$ and $0 \leq \alpha \leq 90^\circ$, respectively. A visualisation of these parameters is shown in Figure 2.

Two frames of reference are considered:

(x, y, z)	Earth-oriented
(x', y', z')	Satellite-oriented

The definition of two frames allows for easier distinction types of movements of the satellite. The AoA is set with respect to the x-axis that remains constant throughout the flight, and in turn defines the orientation of the (x', y', z') frame. The configuration angle, on the other hand, is set with respect to the velocity vector, aligned with the x' component of the (x', y', z') frame.

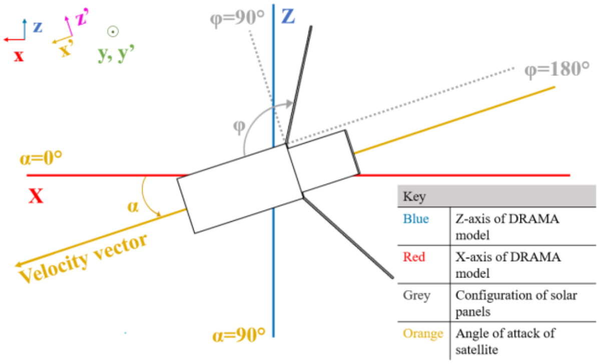

Figure 2: Definition of configuration and Angle of Attack

The geometry modelled consists only of the structural components of the CubeSat, as adding internal components would not only be unadvisable in terms of computational times, but also potentially inaccurate as the selection of components has not yet been finalised. The model is created according to the inputs specified in Table 1, entirely out of Aluminium (Al) 7075 with properties as defined within DRAMA, at initial temperature 27°C and on an orbit defined on the J2000 reference frame as per Table 2. Re-entry is modelled having fixed attitude (not tumbling), with the initial attitude of the satellite consisting of variable AoA, and constant nil bank and slip angles.

Table 1: Geometry parameters

Component	**Chassis**	**Solar panels (each)**
Object type	hollow cuboid	thin cuboid (slat)
Length [m]	0.1	0.00282
Height [m]	0.2	0.21
Width [m]	0.1	0.08
Mass [kg]	1.885	0.1

Table 2: Initial orbital parameters of re-entry trajectory

Element	**Value**
Semi-major axis [km]	6488.3141
Eccentricity [-]	0.001521
Inclination [°]	51.5704
Right Argument of Ascending Node [°]	4.3771
Argument of Perigee [°]	60.8399
True Anomaly [°]	239.3224

To evaluate whether configuration or AoA have a greater effect on the re-entry experiment, the simulation is run for 90°≤φ≤175° in increments of +5°, and 0°≤α≤90° in increments of +10° for each value of φ (18 iterations of φ and 10 iterations of α, resulting in 180 datasets). These increments are small enough to allow for reliable interpolation should this be deemed necessary in the future.

2.2 Assumptions

Certain assumptions and simplifications are established as a result of tool limitations and the stage of development of STRATHcube, declared below:

i. No temperature gradients are found across components.
ii. A temperature of 427°C (below the solidus of Al7075) is set as the model dissolution trigger [8].
iii. The experiment terminates upon first major fragmentation event.

3. Results

This section presents the results obtained through the re-entry simulations conducted in DRAMA, where the conditions under which the first major fragmentation event occurs are the primary areas of focus. Figure 3 shows the range of AoA and SA configurations modelled (a), and the variation of re-entry duration (b), fragmentation altitude (c), and chassis temperature upon fragmentation (d) for the 18 pre-defined angling combinations.

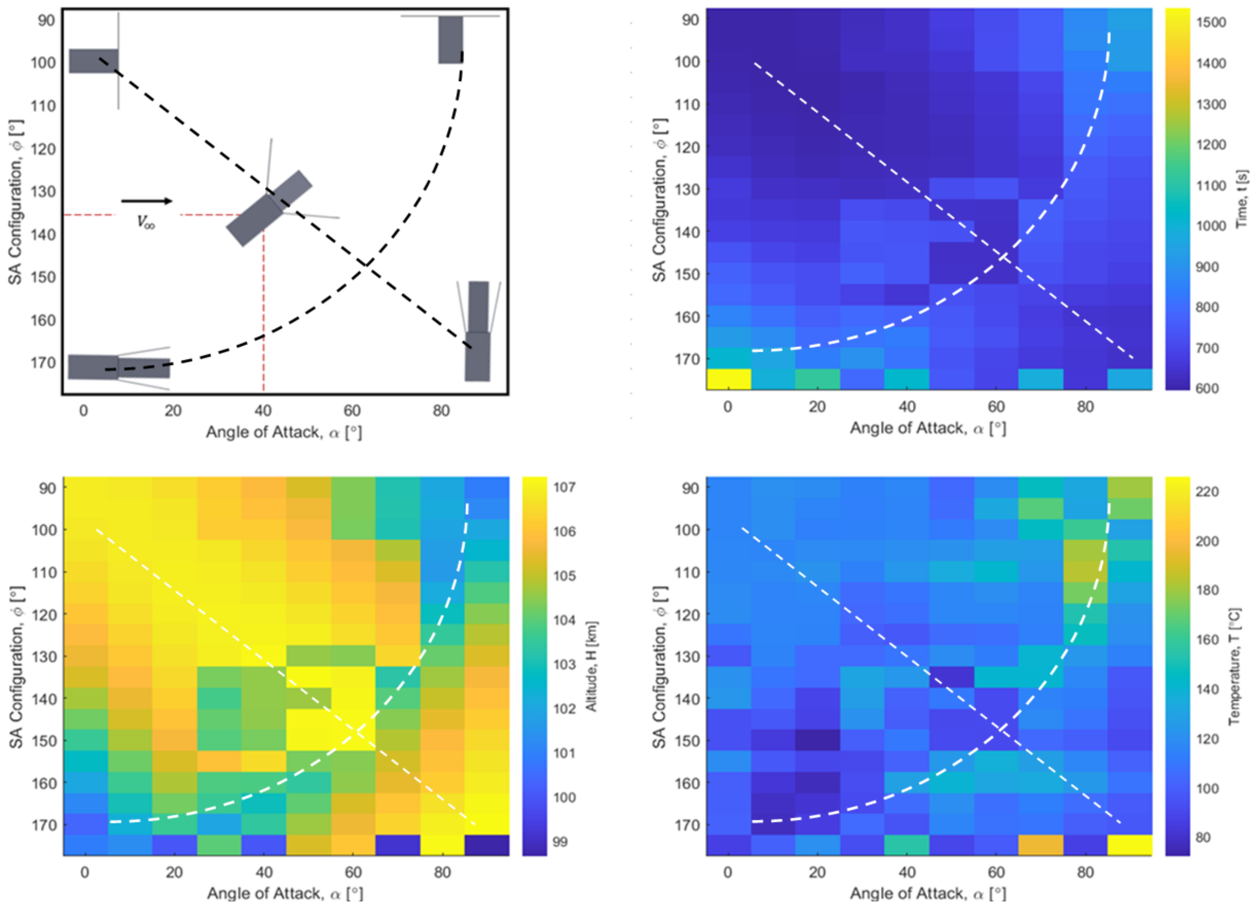

Figure 3: Trajectory and temperature conditions characterising STRATHcube upon fragmentation. In (a), the red dashed line signifies a sample angling combination with respect to the velocity flow. In (a-d), black/white dashed lines represent the two main regions referenced in observations, divided according to the magnitude of wetted area. Region A corresponds to that signified by the straight dashed line (large surface area), whereas region B is defined by the curved dashed line (less surface area).

4. **Discussion**

4.1 Aerothermal Effects

While trajectory parameters offer insight into the conditions under fragmentation and demise take place, temperature imposes a constraint onto the selection of a combination of φ and α, due to the limited operational temperatures of payload components (detailed in Table 3). Hence, the main driver of this analysis is to pinpoint the configuration/AoA combination that produced the lowest temperature at fragmentation. The following key observations are made:

i. The duration of re-entry mostly seems to be dependent on the area exposed to the flow, as evidenced by the earlier fragmentation times with region A compared to region B.

ii. Though shorter re-entry times (region A) are mostly associated with higher fragmentation altitudes, these altitudes are not proportional to the temperatures recorded upon fragmentation, as 3(d) reveals a far wider range of values in region B where low altitudes are observed compared to region A.

An evaluation of the Knudsen number characterising the flow is possible since this quantity is one of the standard aerothermal outputs of DRAMA. It is revealed that all fragmentation events occur at $0.22<Kn<1.07$ in the lower transitional regime. It is thus deduced that aerothermodynamic quantities such as the coefficient of drag, heat flux, and by extension the ballistic coefficient and temperature, vary non-linearly with a body's wetted area re-entering through the transitional region consistently with literature [8].

4.2 Experiment feasibility

As the success of the experiment depends on the collection and transmission of flight data, the operational temperatures of critical components are taken into consideration. As minimum operational temperatures are not relevant in the re-entry environment, preliminary components and their maximum operational temperatures are outlined in Table 3.

Table 3: Operational temperature limits imposed by components

	Function	**Description**	**Maximum Operational Temperature, T_{OP} [°C]**
System	Power and Electronics	Secondary power source (battery)	60
		On-board computer	85
Payload	Data transmission	Analog to Digital Converter	85
		Modem	70
		Antenna	86
	Data collection	Pressure Sensor	55
		Camera	60
		Heat flux Sensor	120
		Raspberry Pi	85
		Thermocouple	260
		Inertia Measurement Unit	85

Thus, the satellite's maximum operational temperature ($T_{OP,max}$) is taken as 55°C. The configuration and AoA should ideally enable the satellite to remain within the operational ranges of these mission critical components for as long as possible.

The lowest chassis temperature is recorded for φ=150° and α=20°, at T=72°C, which would even exceed the pre-defined maximum CubeSat operational temperature adjusted for 20% margin ($T_{OP,max}$ =55°C±20%). The current driver of this system constraint is the pressure sensor; as its function is decoupled from the rest of the payload platform, it may be safe to consider its cease of operation as non-critical to the success of the experiment. Nonetheless, the collection of pressure data is essential to the formulation of a complete, transient re-entry database, introducing a recommendation for consideration and/or development of a more thermally resilient sensor as the design progresses. On a system level, the maximum operational temperature is dictated by the battery with $T_{SYS,max(raw)}$=60°C. Adjusted for an optimistic 20% uncertainty, $T_{SYS,max(unc)}$=72°C, which marginally suggests that the satellite would operate reliably during re-entry until fragmentation with a φ=150° and α=20° configuration. To gain more confidence in this possibility, iterations of high-fidelity thermal modelling are recommended as the design progresses to assess the survivability of the components under the revisions of predicted aerothermal loads. Nonetheless, this investigation is able to reliably inform that aerothermal flux experienced during re-entry has the least impact for this angle combination, informing the next stage of the mission design process with an updated re-entry attitude proposal, visualised in Figure 4.

Whilst the simulations provide a collection of datapoints for pre-defined angles, the relationship of fragmentation temperature and wetted area is more widely represented in Figure 5 for the full range of possible exposed surface areas. This relationship advises the surface area requirements that the mission design should adhere to even after the consolidation of internal components.

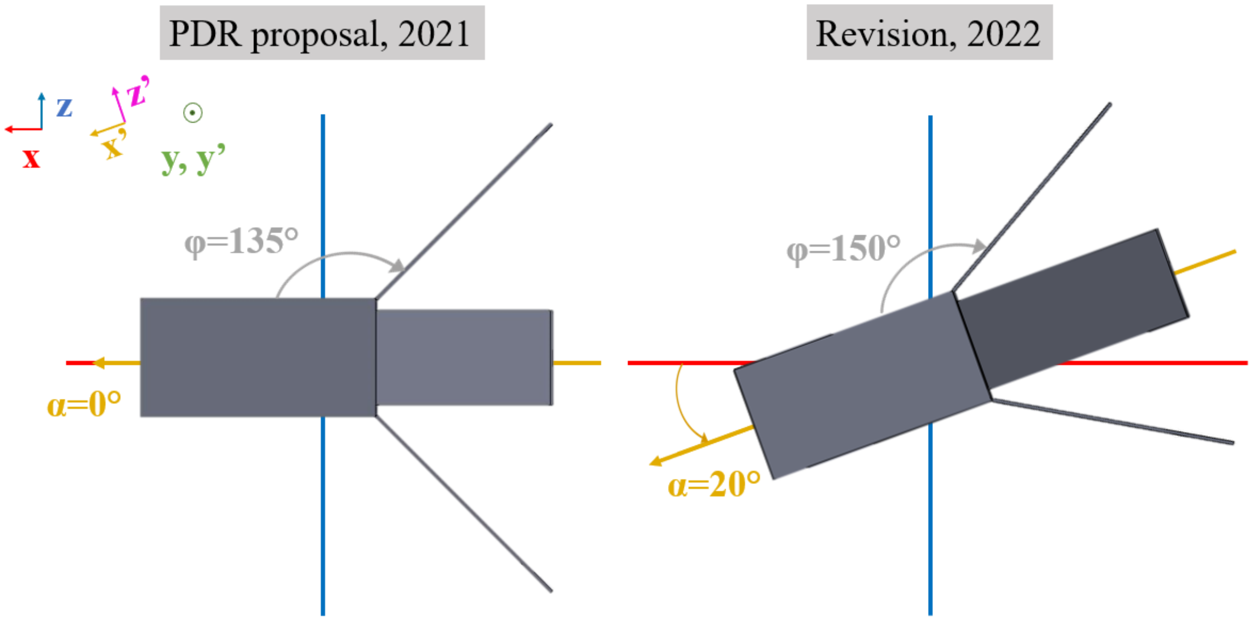

Figure 4: Comparison of Preliminary Design Review (PDR) configuration and AoA proposal to current recommendation

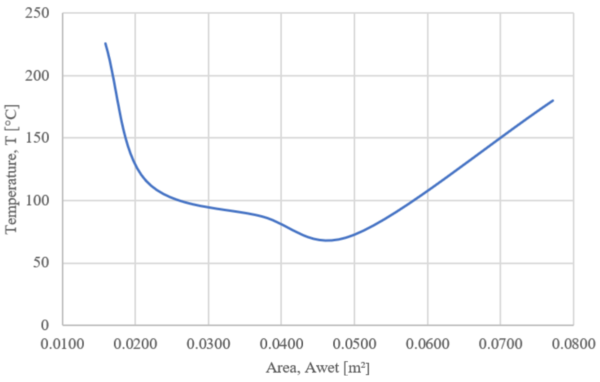

Figure 5: Variation of chassis temperature recorded at fragmentation compared to the initial (prior to any ablation/melting) exposed surface area. While the design of the structure progresses, this provides a useful reference for a target design requirement.

4.3 *Impact of Assumptions*

The implication of using a highly uncertain model is that any results obtained signify a conservative estimate for the duration of the experiment, as DRAMA is constructed such that it offers a "worst-case" scenario in terms of the ground casualty risk predicted. As such, fragmentation is actually expected to occur at higher altitudes than those suggested by the simulations, where temperatures are lower and hence more favourable to the operation of the components. Nonetheless, lack of experimental data limits the possibility of validation of such a suggestion, emphasising on the importance of conservative estimates. Moreover, significant uncertainties characterise the analysis itself due to the assumptions established in Section 2.2.

One of the most impactful assumptions would be that the lowest chassis temperature would also correspond to lowest solar panel temperature at fragmentation. Table 4 outlines the temperature of the panels at the time:

Table 4: Temperature of CubeSat objects upon fragmentation

$T_{chassis}$ [°C]	T_{SP1} [°C]	T_{SP2} [°C]	T_{SP3} [°C]	T_{SP4} [°C]
72	255	157	255	427

It is evident that while the temperature of the panels varies significantly with φ and α, the high temperature differential between the chassis and the panels, would result in an uneven temperature gradient within the body of the CubeSat in a non-lumped mass model, as a result of heat transfer between the panels and the chassis through conduction and radiation. Therefore, suggesting that the mission would survive until fragmentation is perhaps ambitious, as mission-critical components could malfunction earlier. Employing a panel-oriented tool in the next stage of analysis would expose the effect of such temperature gradients with higher reliability compared to object-oriented DRAMA.

4.4 *Future Work*

High-fidelity re-entry analysis of STRATHcube would not only reflect the initial conditions of its re-entry more accurately, but also provide a platform for verification of the predictions obtained through this investigation. Alternatively, the incorporation of a conduction module within the STRATHcube Integrated Systems Tool, developed at the University of Strathclyde, could utilise the heat flux outputs of this analysis, revised material properties and structural configuration inputs to inform the maximum temperature predictions for internal components.

Due to limitations relating to the DRAMA pre-defined fragmentation altitude and the mitigation method employed to represent the behaviour of the joints under high temperatures, it is recommended that further work considers a Monte Carlo parametric analysis of the temperature set as dissolution trigger, namely in the region of 377-477°C, with the upper extremity being the eutectoid temperature of Al7075.

5. **Conclusions**

This analysis explores the effect of solar panel configuration and angle of attack on the re-entry of STRATHcube, with particular focus placed on the feasibility of the secondary payload experiment with respect to the maximum operational limits of payload-critical equipment.

The attitude of re-entry proposed in the PDR (φ=135° and α=0°) is revised. The lowest temperature is reported at T=72°C for φ=150° and α=20°. The employment of this attitude would reduce the temperature at the chassis by 25.5°C compared to the attitude proposed previously, but it would intensify the temperature gradient present within the chassis as a result of heat transfer from the significantly hotter solar panels. Unless the selection of certain components is updated, most of the payload is reluctantly predicted to survive re-entry until fragmentation.

This study relies upon data retrieved through a low-fidelity model, which introduces the implication of high uncertainties due to the aerothermal model and simplified geometry. It is recommended that high-fidelity analysis is conducted to validate the results presented and the attitude proposal that is output.

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