

## EVALUATING AND ADDRESSING POTENTIAL HAZARDS OF FUEL TANKS SURVIVING ATMOSPHERIC REENTRY

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### Abstract

In order to ensure reentering spacecraft do not pose an undue risk to the Earth's population it is important to design satellites and rocket bodies with end of life considerations in mind. In addition to considering the possible consequences of deorbiting a vehicle, consideration must also be given to the possible risks associated with a vehicle failing to become operational or reach its intended orbit. Based on recovered space debris and numerous reentry survivability analyses, fuel tanks are of particular concern in both of these considerations.

Most spacecraft utilize some type of fuel tank as part of their propulsion system. These fuel tanks are most often constructed using stainless steel or titanium and are filled with potentially hazardous substances such as hydrazine and nitrogen tetroxide. For a vehicle which has reached its scheduled end of mission the contents of the tanks are typically depleted. In this scenario the use of stainless steel and titanium results in the tanks posing a risk to people and property due to the high melting point and large heat of ablation of these materials leading to likely survival of the tank during reentry. If a large portion of the fuel is not depleted prior to reentry, there is the added risk of hazardous substance being released when the tank impacts the ground.

This paper presents a discussion of proactive methods which have been utilized by NASA satellite projects to address the risks associated with fuel tanks reentering the atmosphere. In particular it will address the design of a demiseable fuel tank as well as the evaluation of "off the shelf" designs which are selected to burst during reentry.

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## ABSTRACT

In order to ensure reentering spacecraft do not pose an undue risk to the Earth's population, it is important to design satellites and rocket bodies with end-of-life considerations in mind. In addition to the possible consequences of deorbiting a vehicle, consideration must be given to the possible risks associated with a vehicle failing to become operational or to reach its intended orbit. Based on recovered space debris and numerous reentry survivability analyses, fuel tanks are of particular concern in both of these considerations. Most spacecraft utilize some type of fuel tank as part of their propulsion systems. These fuel tanks are most often constructed using stainless steel or titanium and are filled with potentially hazardous substances such as hydrazine and nitrogen tetroxide. For a vehicle that has reached its scheduled end-of mission, the contents of the tanks are typically depleted. In this scenario, the likely survival of a stainless steel or titanium tank during reentry poses a risk to people and property due to the high melting point and large heat-of-ablation of these materials. If a large portion of the fuel is not depleted prior to reentry, there is the added risk of a hazardous substance being released when the tank impacts the ground.

This paper presents a discussion of proactive methods that have been utilized by NASA satellite projects to address the risks associated with fuel tanks reentering the atmosphere. In particular, it will address the design of a demiseable fuel tank, as well as the evaluation of fuel tank designs, which are selected based on whether they burst during reentry.

## 1. INTRODUCTION

The propulsion systems of spacecraft represent a unique and challenging problem when considering risks to the Earth's population. The tanks themselves, such as the Delta 2 second stage tank in Fig. 1, are usually constructed of titanium or stainless steel and often survive reentry, resulting in a possible impact risk to people and property on the ground. In addition the types of fuels used in many of these vehicles are often hazardous, resulting in possible environmental

risks should a spacecraft reenter with significant amounts of fuel on board, as can be seen in Fig. 2. Giving consideration to the risks associated with all parts of a vehicle's life cycle are necessary, whether it be to the vehicle which reenters after it has depleted its fuel supply or the vehicle which fails to reach its desired orbit and reenters with a significant amount of fuel on board. It becomes necessary to evaluate numerous malfunction scenarios associated with these tanks, not only for Earth orbiting vehicles, but also for interplanetary spacecraft.



Figure 1. A 250 kg., stainless steel Delta 2 second stage reentered and landed in Texas in 1997.

Spacecraft designers across NASA have begun to proactively address these issues. For Earth orbiting spacecraft, the Design for Demise (D4D) program has seen NASA Goddard Spaceflight Center (GSFC) working with the NASA Johnson Space Center (JSC) to evaluate the spacecraft bus, payload instruments, and structural components for their potential to survive reentry. For interplanetary spacecraft experiencing mission failure, NASA Jet Propulsion Laboratory (JPL) has worked to limit the environmental impact of loaded fuel tanks by seeking out tank designs that are likely to burst during reentry. Both of these efforts require an iterative process between the spacecraft designers and the JSC Object Reentry Survival Analysis Tool (ORSAT) team.



Figure 2. A Haz Mat team recovers a fuel tank from the 2003 break-up of the Space Shuttle Columbia.

## 2. THE IMPACT RISK

The use of materials with a high likelihood of surviving reentry in fuel tanks stretches back to the early years of launching objects into space. The actual number of tanks that impact the ground is difficult to gauge, since reentry debris that fall on land are rarely identified as space debris. According to data on recovered debris dating back to 1960, nearly half of all debris recovery events have included at least one object described as a metal sphere or a pressure vessel. These tanks are potentially a lethal hazard to the Earth population and are found in the construction of both satellites and launch vehicles. The recognition of this hazard is why fuel tanks are one of the primary components addressed in D4D strategies.

In an attempt to address the survivability of the Gamma-ray Large Area Space Telescope (GLAST) fuel tank, GSFC began addressing reentry survivability risks late in the design process. Due to the size of the vehicle, a propulsion system was included in the baseline design to permit a controlled reentry at end of life [1]. If looking at only those items which have a kinetic energy (KE) >15 J, the propulsion system accounted for more than half of the predicted surviving debris. Removing the propulsion system, thereby removing the risk associated with the fuel tank, coupled with a few other minor design changes, would have resulted in the vehicle being considered compliant for an uncontrolled reentry.

For the Global Precipitation Mission (GPM), a joint NASA and Japanese Aerospace Exploration Agency project to follow the Tropical Rainfall Measurement Mission (TRMM), designers at GSFC took a novel approach to the design of their vehicle. Much like a typical mission establishes mass and power budgets for

the various components of its vehicle, the GPM team established a debris casualty area (DCA) budget for the various subsystems of the vehicle. Since propulsion subsystems are typically a large source of DCA, it was necessary to study the available options for fuel tanks. This led to an extensive collaboration between the GSFC GPM design team and the JSC ORSAT team, beginning in mid 2002, with an extensive study of fuel tank survivability.

The GPM was in the early stages of its design, so the initial phase of the study evaluated generic spacecraft, based on rough estimates of the planned GPM design utilizing a spherical fuel tank. The purpose of this phase of the study was to determine materials that would likely demise during reentry, while also looking at varying wall thicknesses to set a baseline for the tank selection. As expected, the tanks containing stainless steel or titanium were predicted to survive. Those made of aluminum could be made to demise if the proper wall thicknesses were used. While there had been previous instances of aluminum being used to construct hydrazine tanks, it had been limited to vehicles, such as rocket bodies, where the mission lifetime was short. The GPM mission called for a 25-year lifetime, leading to concerns regarding the compatibility of aluminum and hydrazine for such a long time.

Since GPM was designed to be similar to the TRMM, it was decided to use the TRMM's geometry and trajectory initial condition as a baseline for further analysis. This follow-up set of analyses varied the size (0.46 m<sup>3</sup> or 0.92 m<sup>3</sup>), shape (cylinder or sphere), material composition (monolithic or composite), and the break-up point of the vehicle when the tank was exposed to heating. The results from this study indicated that the most demiseable tank would be an aluminum shell with a composite overwrap and an internal aluminum propellant management device [2]. While the ORSAT team studied the survivability of the tanks, GSFC undertook a series of materials evaluation tests to address the concerns regarding the long term exposure of aluminum to hydrazine. While the final design for GPM required it to undertake a controlled reentry, the fully demiseable fuel tank, which resulted from these efforts, is a component that is potentially useful to generations of future spacecraft.

## 3. THE ENVIRONMENTAL RISK

The potential uncontrolled reentry of the disabled USA-193 spacecraft in 2008 was one of the most widely recognized reentry risks since 2001. The titanium fuel tank at the heart of the vehicle (Fig. 3), containing approximately 450 kg of frozen hydrazine, was predicted by multiple, independent, detailed

analyses to have the potential to survive reentry intact (as is the typical result for empty tanks), allowing its contents to vaporize and pose a hazard to people on Earth. While the immediate risk for this tank was the impacting body, a concern arose for the environmental damage around the impact site and the potential for an additional health hazard to people. Had this tank been made of a material with a lower melting temperature, the decision to destroy it prior to reentry would have been unnecessary. As a result of this event, the consideration of the possible environmental impacts related to reentering fuel tanks was recognized as being important.



Figure 3. Titanium fuel tank design used for the USA-193 spacecraft.

Leading the way in NASA's effort to reduce environmental risks were project teams from JPL who were working on the development of the Juno and Mars Science Laboratory (MSL) spacecraft. Both of these missions are interplanetary, and, thus, not normally pertinent to end-of-life reentry risk issues. Instead, the focus for these vehicles was on what would happen if the spacecraft failed to leave Earth orbit. The result of this scenario would be vehicles with large amounts of fuel that would eventually reenter the atmosphere, a situation that is not usually considered during the design phase. This consideration led to a number of studies by the JSC ORSAT team, based on numerous satellite tank designs, with the goal to determine whether it was likely that fuel from these tanks would reach the ground should the vehicle reenter Earth's atmosphere. Tab. 1 shows the results of analyses to determine if the fuel tanks were likely to

burst during reentry, as well as the DCA for the empty tanks.

Table 1. Results of tank bursting study

	122 km Initial Altitude		
	Burst Altitude (km) with fuel and pressure	Altitude Burst (km) with fuel	Empty Tank Debris Casualty Area (m <sup>2</sup> )
MSL Descent	61.1	60.9	1.4
MSL Cruise	74.2	73.8	1.1
Juno	56.7	56.3	2.0
MRO	51.3	44.2	3.4
CGRO	57.0	47.4	2.3
Cassini	71.7	64.1	1.5

	78 km Initial Altitude		
	Altitude Burst (km) with fuel and pressure	Altitude Burst (km) with fuel	Empty Tank Debris Casualty Area (m <sup>2</sup> )
MSL Descent	60.9	60.9	1.4
MSL Cruise	72.5	72.3	1.1
Juno	55.0	54.5	2.0
MRO	46.5	37.2	3.4
CGRO	54.5	43.4	2.3
Cassini	70.3	63.7	1.5

The initial studies concluded that if the tanks broke apart from the vehicle in such a way that the fuel and pressurant contained inside were unable to vent, then the tanks would burst, causing the contents to disperse into the atmosphere. The team at JPL took this one step further and looked at ways to predict the amount of fuel left in the tank should the lines be open or only partially blocked. The result of this further analysis is that, had Juno not successfully left Earth orbit, there was a risk that its fuel tanks would have impacted the ground containing approximately 38 kg of liquid hydrazine. For MSL the picture is more benign, in that, should it fail to leave Earth orbit, the tank is not likely to have any residual fuel left in its tank when it impacts the ground [3]. In both of these cases, the analysis took place late in the design phase and was done mainly to understand the existing risk associated with those vehicles.

For the EXO Mars 2016 vehicle, consideration of possible tank survival took place earlier in the design phase and is ongoing. For this vehicle, the JPL team presented a description of the preliminary tank design to the JSC ORSAT team prior to the design being finalized. This mission utilizes a bi-propellant system, which results in the vehicle having a mono-methyl hydrazine tank, as well as a nitrogen tetroxide tank. As in the earlier study, analysis was performed to determine if the tanks were likely to burst should they break away from the vehicle in a manner that prevents the fuel from escaping. The analysis on these tanks also took into account the possibility of the attitude of the tanks being stable. Preliminary results indicate that the tanks are likely to burst if there is no way for the fuel to escape, or the tank wall is likely to be breached, should the attitude remain stable.

#### 4. CONCLUSIONS

The use of high-melting temperature materials in the manufacture of fuel tanks leads to two different types of hazardous situations should these tanks reach the ground. The sheer size and mass of these tanks results in them being a potential hazard should they impact someone or something on the Earth's surface. The possibility that these tanks could contain large quantities of fuel when they impact creates an additional hazard to the environment in the immediate vicinity of the impact location.

Efforts to minimize these risks require careful consideration early in the vehicle's design phase. Had the GLAST project team followed the current safety standards they could have ignored the risk associated with objects that impacted with a low KE. This would have permitted them to completely remove the propulsion system, thereby eliminating the associated impact risk. GPM was able to completely remove the risk by designing a tank in such a way that it fully demised. In order to reduce the environmental risk associated with fuel tanks, JPL is proactively working on the design of fuel tanks for interplanetary spacecraft to ensure that little to no fuel impacts the ground should the vehicle unexpectedly reenter.

By implementing a D4D strategy from the onset of a mission, the cost of compliance with safety standards can be minimized, especially when it comes to propulsion systems. In the case of GLAST, this would have resulted in the elimination of an entire subsystem, permitting more mass for payloads. For future vehicles, consideration of all aspects of the vehicle's lifetime could result in a decision that will lead to an environment on Earth that is not at risk due to the potential reentry of objects launched into space.

#### 5. REFERENCES

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