Design for Minimum Casualty Area – The IXPE Case

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ABSTRACT

The Imaging X-Ray Polarimetry Explorer (IXPE) is a new international space observatory in NASA's Small Explorer program, designed in a collaboration between the Italian Space Agency and NASA's Marshall Space Flight Center, and built by Ball Aerospace. IXPE has an expected launch in November 2021, to a 600-km altitude equatorial orbit. IXPE is an astrophysics mission using three telescope assemblies to measure the polarization of cosmic X-rays. Each assembly is composed of a mirror module assembly (MMA) with 24 nested nickel-cobalt cylindrical shells and a unique, polarization-sensitive, gas pixel detector (GPD) within the detector unit (DU). As a NASA mission, IXPE must adhere to the orbital debris mitigation requirements specified in NASA Standard 8719.14 [1]; in the present work, we will only discuss reentry human casualty risk.

As initially designed, the IXPE observatory exceeded NASA's casualty risk threshold. IXPE does not include a propulsion system to perform a controlled reentry at the end of mission to mitigate the ground casualty risk. To reduce the risk from the uncontrolled reentry of this observatory, the IXPE design team worked with the NASA Orbital Debris Program Office to reduce the debris casualty area through design-for-demise and containment methods. The flight design of IXPE is now compliant with the ground casualty risk requirement at a casualty probability of 1:13,100 compared to a casualty requirement of better than 1:10,000.

1. INTRODUCTION

The Imaging X-ray Polarimetry Explorer (IXPE) is a NASA Small Explorer x-ray astrophysics mission led by NASA Marshall Space Flight Center (MSFC). [1] The IXPE Observatory is a single flight element launched to a circular, low Earth orbit (LEO) at an altitude of 600 km and an inclination of ~0.2 degrees on a Falcon 9 launch vehicle. IXPE is baselined as a 2-year mission with extended mission options. IXPE will measure the spatial, spectral, timing, and polarization state (degree and angle) of x-rays from known astrophysical targets.

The IXPE Observatory consists of spacecraft and payload modules built up in parallel to form the Observatory during system integration and test. Figure 1 shows a photo of the integrated Observatory in its stowed configuration. A view of the deployed IXPE Observatory is shown in Figure 2. When deployed, IXPE is 5.2 m from the bottom of the spacecraft structure to the top of the payload and is 1.1 m in diameter. The solar panels span 2.7 m when deployed. The Observatory launch mass is approximately 333 kg. The payload is mounted on the +Z face of the spacecraft structure (top deck). This simplifies alignment and integration and minimizes mass by providing the shortest possible load paths. IXPE's payload is a set of three identical, imaging, x-ray polarimetry telescopes mounted on a common optical bench and co-aligned with the pointing axis of the spacecraft. Each 4-m focal length telescope operates independently and is comprised of a mirror module assembly (MMA) (grazing incidence X-ray optics) [2] and a polarization-sensitive, gas pixel detector (GPD)-based, imaging detector unit (DU). Each MMA is a bonded assembly consisting of 24 concentric, nickel-cobalt, mirror shells, front and back spiders to hold the shells, inner and outer housings, and other elements. The focal length is achieved using a deployable, coilable boom. The MMAs are mounted in the mirror module support structure (MMSS) deck. The IXPE spacecraft is based on Ball's BCP-small spacecraft product line. [3]

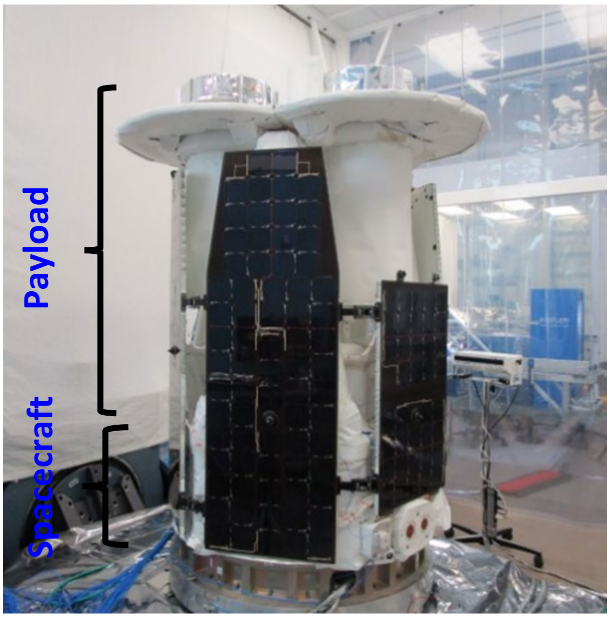

Figure 1. IXPE Observatory in Stowed Configuration (Credit: Ball Aerospace)

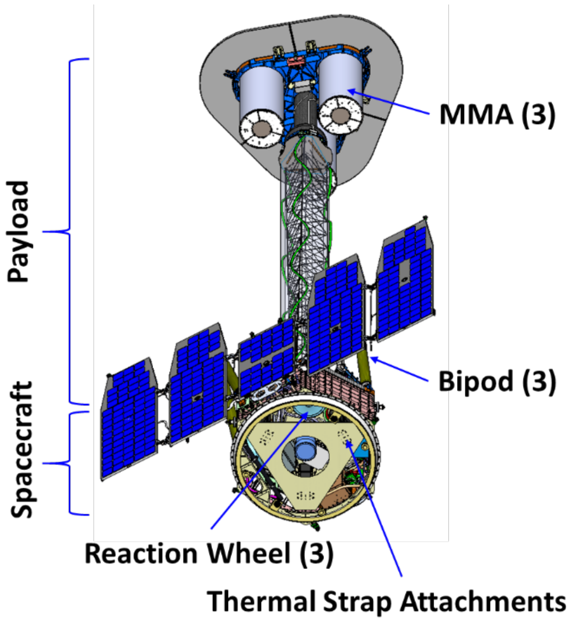

Figure 2. IXPE Observatory in Deployed Configuration (Credit: Ball Aerospace)

2. BACKGROUND ON NASA POLICY AND MITIGATION PRACTICES

All United States agencies involved in the launch or operation of space objects (spacecraft or upper stages) since 2001 have been expected to follow the United States Orbital Debris Mitigation Standard Practices (ODMSP), which includes public risk acceptance criteria for the destructive entry of any space object.[4] NASA's governing document to enforce requirements consistent with the ODMSP is the NASA Technical Standard 8719.14 "Process for Limiting Orbital Debris", currently under evolution from Revision B to Revision C.[5] Revision C captures the most recent (December 2019) changes to the ODMSP.[6] However, NASA's practices for assuring ground safety originated before the first ODMSP, within NASA Safety Standard (NSS) 1740.14 in August 1995. [7]

The ODMSP acceptable risk thresholds derive from detailed studies supporting the work of the Range Commanders' Council (RCC), documented in the RCC Handbook 321.[8] These studies found that steel spheres with 15 joules or less of kinetic energy cannot cause an injury sufficient (in some limited cases) to require medical treatment. ODMSP risk policy therefore counts any falling debris item with terminal energy greater than 15 joules as being hazardous.

Further, per RCC guidelines, the acceptable risk of any injury to any individual from any hazardous event is a maximum of one chance in ten thousand (also known as the Expectation of Casualty, denoted E_c). The ODMSP has adopted this threshold E_c for the re-entry of any single space object. NASA enforced these limits even prior to the first ODMSP release. Both the 15-joule threshold and the 1:10000 acceptable probability limit have propagated to become the common practice wherever any of the world's space agencies' safety policies specify either energy or probability limits.

NASA standards enforce a methodology to prove compliance with the net risk. These methods include accepted standard processes for finding the size and count of all expected fragments with 15 joule or greater terminal kinetic energy, and the probability that any of them will intercept a human. In preliminary design, each of these calculations is performed under several key mandated assumptions, using NASA's publicly-available Debris Assessment Software (DAS).[9] Key assumptions include the expected altitude at which an entering spacecraft will fragment, expected population growth, average cross section of a human, weighted probabilities of spacecraft entry at every possible latitude and certain nuances, such as the lack of sheltering effects, and conversely the lack of any amplification of risk from exceptionally energetic debris strikes of buildings or nearby dirt—are not included in this preliminary screening tool. Whenever the mandated assumptions lead to a violation of the E_c threshold in DAS, special analyses are warranted. If significant problems are spotted early enough, the agency's analytical entry specialists and more advanced tools are put at the service of the design team to evolve the preliminary design into one that meets all safety goals. This was the case with the IXPE spacecraft.

3. REENTRY MODELS

The NASA Orbital Debris Program Office (ODPO) maintains two pieces of reentry risk assessment software: the Object Reentry Survival Analysis Tool (ORSAT) and DAS. While these tools share many features, they are designed for slightly different purposes. ORSAT is a full-featured, object-oriented, reentry model that allows the experienced analyst greater freedom in modeling choices, while DAS is intended for end-users to obtain quick, conservative results for orbital debris applications. A result of noncompliance in DAS indicates that a higher-fidelity model such as ORSAT may be needed to determine if a spacecraft is in fact compliant with reentry risk standards.

3.1 ORSAT-- Version 6.2.1

ORSAT was developed by NASA JSC and originally released in 1993. It was developed as a high-fidelity tool to model atmospheric conditions, trajectory, aeroheating, and aerodynamics of a reentering object and determine if and when the object demises. If an object survives, ORSAT calculates the casualty area and impact kinetic energy. [10] The latest version of ORSAT, v. 6.2.1 incorporates updated atmospheric models and a partial ablation model for fiber-reinforce polymer composites.

By modeling a spacecraft as a collection of components that are all released at a specified breakup altitude, ORSAT can track the trajectory and demise of each individual component and calculate a total casualty area for the spacecraft.

Each component is modeled as a shape primitive (sphere, cylinder, box, plate, or disk) of appropriate dimensions and material. For spheres, cylinders, and boxes, heat conduction through the object can be calculated by using a 1D or 2D mesh. In addition, an object may have multiple material layers, and the thermal conductivity and specific heat capacity of each layer can be accounted for. Plates and disks, on the other hand, are handled as lump mass objects, where the demise of an object is determined by the inequality in Eq. 3.1, where Q_{abs} is the total absorbed thermal energy, H_{fus} is either the heat of fusion or heat of vaporization, T_0 is the starting temperature of the component, T_{melt} is the melting/vaporization temperature, and c_p is the specific heat capacity. Once a mesh node reaches this condition, ORSAT assumes that the material associated with that node has either vaporized or aerosolized and the node is removed from the component. Once all mesh nodes have demised, the entire object is considered to have demised. If not all mesh nodes demise, the object impacts the ground with a mass and size diminished by the number of mesh nodes lost.

$$Q_{abs} \geq H_{fus} + \int_{T_0}^{T_{melt}} c_p(T)\, dT \qquad 3.1$$

ORSAT can calculate the thermal energy deposited in a component from many different sources: aerothermal using either the Detra-Kemp-Riddell [15] or the Fay-Riddell [16] model, oxidation, and shock layer radiation using either the Tauber-Sutton [17] or Jones-Park [18] model.

3.2 DAS – Version 3.1

DAS is the official means of assessing compliance with NASA Orbital Debris Mitigation Requirements as set forth in NASA STD 8719.14. These requirements include limits on postmission orbital lifetime (the "25-year rule"), large object collision risk, mission related debris, and the limit on expectation of casualty. [9]

The destructive entry routines in DAS are derived from those in ORSAT, with certain simplifications, such as a lumped thermal mass model (i.e., only one mesh node), and only four shape primitives, namely: spheres, boxes, flat plates, and cylinders. These simplifications make it easier for developers and operators to develop and run a credible model.

DAS Version 3.1 was released in 2020 and included the latest version of the Orbital Debris Engineering Model (ORDEM), version 3.1.2, as well as certain updates to the entry routines reflecting the changes to ORSAT 6.2.1. [11]

4. REENTRY CASUALTY RISK CALCULATION

As stated in the background section, the calculation of the risk to the ground population resulting from a spacecraft entry includes both the determination of all expected fragments with greater than 15 joules of terminal kinetic energy and the calculation of the collective probability that any of these fragments will strike a human.

4.1 Surviving Debris Calculation

To determine the quantity, individual terminal energy, and size of each surviving fragment of a re-entering spacecraft or stage, it is necessary to conduct a detailed aerothermal analysis of every component of the spacecraft. To do this, during the design phase each spacecraft is modeled as a series of nested primitive objects of simplified geometry and of detailed material type, mass, and thickness. The creation of this "object model" is a time-consuming effort requiring significant expertise. In particular, the required expertise increases significantly once one moves from a publicly available entry risk screening tool such as DAS to more complex models (such as ORSAT). Such elevated expertise anticipates radiative and conductive internal heat transport, accurate ballistic properties, and especially the nuanced assignment of nodes and layers within each object. This last facet of the model is similar to the construction of a simple finite element model of each object. There may be scores—or, in rare cases hundreds—of primitive component objects in any spacecraft's object model.

The object model is then subjected to detailed (and highly coupled) ballistic and aerothermal calculations. The ballistics of any component (or nested grouping of components, in a "parent" object) is calculated as a function of its mass, area, aerodynamic state (tumbling or aero-stabilized), current surrounding air density, and angle of attack. This ballistic forecast generates an aerothermal heating rate that is material- and temperature-dependent. Each object on the spacecraft's exterior is modeled to re-radiate heat (inwards or outwards) or to ablate. Where any object layer reaches the melting point of the material, that layer is modeled to ablate away completely during the narrow time increment. When ablation occurs, the mass and area of the modeled component both change, affecting future ballistics.

This dynamic adjustment of parameters is conducted under a Runge-Kutta scheme to assure a smooth process. When the last layer of a bounding "parent" structure (say, a battery box) is observed to ablate away, all "child" components inside that structure (the batteries) are modeled to be instantly free-flying at the same altitude and ballistic trajectory as the parent object. This successive demise of outer parent structures and release of their contained child objects cascades until all components have either fully ablated away or have hit the ground. Every object hitting the ground with 15 joules or more of kinetic energy is assumed to be a risk to the general population.

4.2 Calculation of Population Risk

Probability of impact is assessed by calculating the ratio of the impact area that is potentially dangerous to the total possible impact area. To first order, the total possible impact area is the surface of the Earth that lies between the latitude extremes of the orbit (+/- the orbit inclination), although there are many factors that affect how much weight one assigns to each latitude band. The area that is dangerous is the sum of all surviving debris' hazardous areas. This sum is called the Debris Casualty Area (DCA). The key factor in calculating a debris item's hazardous area is to recognize that the DCA of an object includes the size of the human it might hit, not just the (typically much smaller) object itself. Even if each hazardous debris item had zero cross sectional area, its DCA would still be the average size of a human being when seen from above. Per longstanding practice, the average cross-sectional area of a human, averaged over all human sizes and over seated, standing, and prone positions is 0.28 square meters. This represents the minimum DCA per surviving fragment. The actual casualty area is uniquely calculated for each debris item, accounting for the prospect that any part of the debris item might hit any part of the human. The DCA is therefore calculated within the boundary of a human extended by the radius of the debris item. The sum of all unique component DCA's is the total DCA, typically many square meters.

The probability is represented by the concept of E_c that combines the cumulative DCA of the fragments with the likelihood that the debris will land at any given (very narrow) latitude band, weighted by the forecast future population density (persons per square meter) at that latitude. This last parameter is calculated from the Gridded Population of the World, currently in revision 4 (GPW4: produced by the Socioeconomic Data and Applications Center (SEDAC) of Columbia University) [12]. This grid is adjusted cell-by-cell with future growth forecasts generated from the US Census Bureau International Data Base (IDB) and United Nations World Population Prospects (WPP) projections for the years 2010-2070. [13] The latitude-based population density forecast for the year 2021 can be seen in Fig. 3.

All NASA spacecraft are analyzed in the early design phase for expected entry risk. If the screening in DAS shows too high an E_c, additional steps are triggered to bring the spacecraft into compliance with the ODMSP and NASA standards. These steps include 1) analysis under higher-fidelity, less conservative ORSAT modeling, 2) adjustment of orbit lifetime and inclination to expose the footprint to a lower population density, 3) redesign to include targeted entry to an unpopulated region, or most preferably, 4) redesign of the spacecraft to eliminate contributors to the DCA. This last scenario is commonly called "Design for Demise" or D4D. IXPE was an exemplary case of this practice.

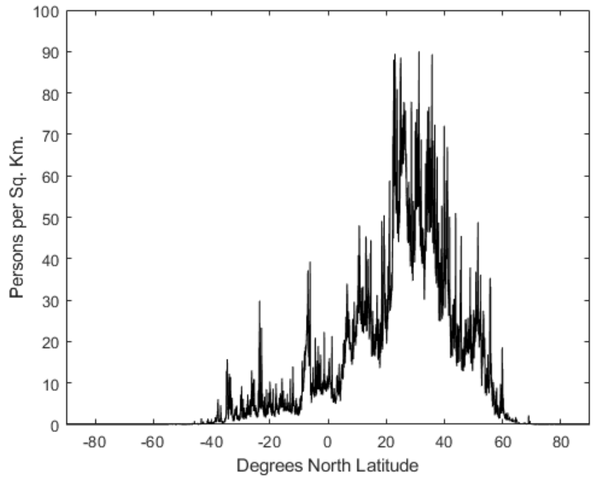

Figure 3. 2021 Population Density by Latitude

5. IXPE COMPONENTS

IXPE was built up from a payload module and a spacecraft bus module that where integrated together to form the Observatory (also simply called the 'spacecraft'). The IXPE spacecraft consists of a deployed end and a spacecraft end separated by a boom. The deployed end includes the three MMAs while the spacecraft end includes the majority of the spacecraft components along with the instrument.

There have been multiple assessments of the re-entry probability of the components of the IXPE spacecraft. A total of 93 individual elements/parts were modeled in the initial analyses during the Concept Study (Phase A). Table 1 (see Appendix) shows the surviving components as the analyses progressed, design matured, and steps were taken to minimize the number of components that reenter.

The ORSAT analysis required engineering and modeling expertise to model the complex structures found in IXPE. Some box-like components were modeled as cylinders, and other similar changes were made, following rules set forward in *Best Practices for Reentry Analysis in DAS* [14].

Following these simpler analysis changes, project work started during Phase B to conduct trades to reduce the number of reentering elements. At the start of Phase B, the battery and MMAs were subject to trades.

5.1 Mirror Module Assembly

The 3 MMAs comprising the IXPE payload were each initially modeled as 24 independent cylinders made of high-temperature material. Consequently, DAS and ORSAT analysis indicated that each of these cylinders (72 in all) would survive to ground impact, contributing to tens of square meters of DCA. The key factor for determining how the MMA structure fragmented was the originally designed aluminum 'spider' at the end of each assembly. The IXPE project altered the design based on these preliminary results by substituting this piece for stainless steel and ensuring the MMA remained as one fragment through to ground impact, thus resulting in a DCA contribution reduction of approximately 3 m^2.

5.2 Battery Box

The IXPE design in the 2016 Concept Status Report used a battery design based on 8 large cells. The large cells making up the battery had stainless steel casings and were enclosed in an aluminum frame. All eight battery cells were assessed to survive re-entry. The IXPE project moved to a small-cell battery design (128 individual cells) in an aluminum enclosure. Follow-up analysis showed the small-cell design resulted in full demise of the battery going from eight re-entering elements to zero.

5.3 Balance Masses

The baseline design bookkept a 1 kg balance mass fabricated from tungsten. In subsequent assessments, this component was changed to stainless steel which also was assessed to survive re-entry. In the most recent assessment, the balance mass material has been changed to copper which demises during re-entry.

5.4 Other Components

During the 2018 and 2019 analyses, the x-ray calibration source holders were found to survive re-entry. The material properties were checked and updated to the as-built source holder materials. The source holders now are assessed to demise during re-entry.

The remaining surviving components from the reentry analysis of the IXPE spacecraft are the Reaction Wheel Rotors (3 total), the MMA (3 total), bipod top bracket (3 total), and thermal straps (~80 total). Modelling indicates that these objects all separate when the main body demises. The total DCA for the IXPE spacecraft is reduced from the previous result to 5.90 m^2 with the final updates.

6. ORSAT ANALYSIS AND RESULTS

Reentry of the IXPE spacecraft was considered to begin at an altitude of 122 km, with catastrophic breakup of the main body of the spacecraft occurring at an altitude of 78 km. The IXPE spacecraft was modeled as a 312 kg aluminum cylinder with diameter 1.1 m and length 5.2 m. An initial velocity (relative to the atmosphere) of 7356 m/s was used based on an orbital inclination of 0.2°; the initial flight path angle was assumed to be -0.1°.

The fragments were typically modeled using a 1D thermal conduction model, except for those components that were thermally "thin" (which were then modeled using a lumped mass approach). For components that survived to ground impact or that were analyzed as demising below 70 km altitude, the number of nodes used in the thermal analysis was varied to establish a more robust survivability model. None of the surviving components had kinetic energy that varied significantly with the number of nodes selected in this analysis.

The spacecraft model comprised 93 unique components totaling 257.5 kg, or 89% of the total mass of the spacecraft. Of these modeled components, 4 unique components (with total quantity 89) survived reentry to impact the ground, and 3 unique fragments (with total quantity 9) impacted with a kinetic energy that exceeded the casualty threshold of 15 J, set in the ODMSP. These surviving components resulted in a total DCA of 5.9 m^2. For an equatorial orbit reentry in the year 2039, this DCA results in a casualty risk of 1 in 13,300.

7. CONCLUSIONS

The IXPE spacecraft is scheduled to launch in late 2021 to a 600 kilometer, 0.2-degree inclination orbit on a SpaceX Falcon 9 rocket. Over the course of five years of cooperation between the NASA Orbital Debris Program Office, Ball Aerospace, and the NASA Marshall Space Flight Center, the mission has modified both its hardware and its mission orbit to successfully mitigate excessive reentry casualty risk. This reduced expectation of casualty of approximately 1:13,300 (from an original estimate of nearly 1:3000) is compliant with the NASA Orbital Debris Mitigation Requirements and is an acceptably low risk to human safety, avoiding the need for costly re-design of propulsion systems and a controlled de-orbit at end of mission. This collaborative effort is a positive example of the benefits of design for demise and design for minimum casualty risk, leading to reduced costs for the mission while meeting the orbital debris mitigation requirements.

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9. APPENDIX

Table 1. List of surviving components from the IXPE Observatory

Analysis Cycle → Component Name ↓	**CSR ODAR (July 2016)***	**PDR ODAR (May 2018)**	**CDR ODAR (Oct 2018)**	**Post-CDR (Dec 2019)**	**Final ODAR (June 2021)**
Balance mass	0.484	0.48	0.484	0.484	
Battery cells	3.808				
Rotor – reaction wheel	1.638	1.81	1.812	1.812	2.05
MMA Inner telescope shell	3.024				
Telescope shell 2	2.997				
Telescope shell 3	2.970				
Telescope shell 4	2.945				
Telescope shell 5	2.919				
Telescope shell 6	2.895				
Telescope shell 7	2.868				
Telescope front spider	2.388				
MMA		3.00	3.000	3.000	3.00
Sources 2		0.00	0.00		
Sources 3		1.18	1.184	1.184	
Thermal strap graphite				0	0
Bipod top bracket				0.478	0.48
Debris Casualty Area	**28.94**	**6.49**	**6.49**	**6.96**	**5.90**
Casualty Risk	**1 : 3190**	**1 : 14411**	**1 : 14411**	**1 : 10,101**	**1 : 13,300**
* DAS v2.0.2					

Note: For components where no entry is present in the table for later ODAR milestones, the component was either successfully redesigned to no longer survive reentry, or later designs incorporated features to prevent individual components from contributing to the Debris Casualty Area – such as the MMA surviving as an intact assembly, eliminating individual contributions from the telescope shells and spider.