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NPSAT1: ASSESSMENT OF RISK FOR HUMAN CASUALTY FROM ATMOSPHERIC REENTRY

by

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March 2016

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The United States government, through the Department of Defense and the National Aeronautics and Space Administration, has established clear guidelines that limit the acceptability of orbital debris fragments striking the surface of the Earth. This thesis addresses both the survivability of the soon-to-be-launched NPSAT1 satellite on its eventual reentry into the earth's atmosphere, and any potential risk to the human populace that may result. After reviewing the history of tracking objects in space, and the policies in place to limit the creation of and risk presented by orbital debris, this research analyzes each of NPSAT1's individual components for its uncontrolled reentry into the earth's atmosphere. The analysis conducted in this paper shows that although a few pieces of debris from NPSAT1 would strike the earth's surface with varying degrees of impact energy, these impacts are not expected to exceed the standards set forth by the Department of Defense.

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NPSAT1: ASSESSMENT OF RISK FOR HUMAN CASUALTY FROM ATMOSPHERIC REENTRY

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TABLE OF CONTENTS

LIST OF FIGURES

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LIST OF TABLES

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LIST OF ACRONYMS AND ABBREVIATIONS

ACS	Attitude Control System
AFI	Air Force Instruction
AIAA	American Institute of Aeronautics and Astronautics
CAD	Computer Aided Design
CCAFS	Cape Canaveral Air Force Station
CDH	Command and Data Handler
CFR	Code of Federal Regulations
COLA	Collision Avoidance
CSM	Conjunction Summary Message
CSV	Comma Separated Values
DAS	Debris Assessment Software
DOD	Department of Defense
DODI	Department of Defense Instruction
DOT	Department of Transportation
EMI	Electromagnetic Interference
EOLP	End of Life Plan
EUV	Extreme Ultra-Violet
FAA	Federal Aviation Administration
GPW	Gridded Population of the World
HEO	High Earth Orbit
HF	High Frequency
IDB	International Data Base
JFCC	Joint Functional Component Command
JSpOC	Joint Space Operations Center
KKV	Kinetic Kill Vehicle
LEO	Low Earth Orbit
MC3	Mobile CubeSat Command and Control
MEO	Medium Earth Orbit
MSL	Mean Sea Level
NASA	National Aeronautics and Space Administration

NASA-STD	NASA Standard
NHBK	NASA Handbook
NOAA	National Oceanic and Atmospheric Administration
NORAD	North American Aerospace Defense Command
NPR	NASA Procedural Requirement
NPS	Naval Postgraduate School
NPSAT1	NPS Spacecraft Architecture and Technology Demonstration Satellite
NRL	Naval Research Lab
NSSCC	National Space Surveillance Control Center
NSTT	NanoSat Terminator Tape
ODMSP	Orbital Debris Mitigation Standard Practices
ODPO	Orbital Debris Program Office
ORSAT	Orbital Reentry Survival Analysis Tool
SAO	Smithsonian Astrophysical Observatory
SDAR	Space Debris Assessment Report
SGP	Simplified General Perturbation
SGP4	Fourth variant of the SGP code
SPADATS	Space Detection and Tracking System
SPASUR	Space Surveillance
SSN	Space Surveillance Network
STP	Space Test Program
TLE	Two Line Element
U.S.	United States
USSTRATCOM	U.S. Strategic Command
UV	Ultra-Violet
ZULU	NATO time zone indicator for Universal Time

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I. INTRODUCTION

Since the launch of Sputnik I, Earth's orbits have been populated by man-made satellites transmitting military, scientific, and commercial data to their respective ground stations below. While some are designed to operate for over 20 years, these satellites will eventually reach the end of their lifetimes. Depending on their orbit, and in compliance with certain United States (U.S.) policies, some spacecraft must be removed from their orbital positions and properly disposed of by their operators, reducing the potential for an on-orbit collision and allowing those positions to become available for other programs. This disposal of a satellite is often a decision that is made with respect to the specific orbital regime in which it has been operating.

The orbital regimes surrounding earth are generally divided into three sequential regions: Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geosynchronous Orbit (GEO) (Figure 1). Satellites operating within LEO, ranging from approximately 180 kilometers to 2,000 kilometers (km) in altitude [1], are typically disposed of by purposefully injecting the spacecraft back into the earth's atmosphere; a process known as atmospheric reentry. In the MEO and GEO regimes (2,000 km to 35,780 km and above [1]), the disposal process involves placing the spacecraft into what is known as a disposal orbit, an orbit typically 300 km above the original. In either case, the spacecraft is drained of its various stored energy (e.g., battery charge, stored fuel) to mitigate the possibility of an explosion.

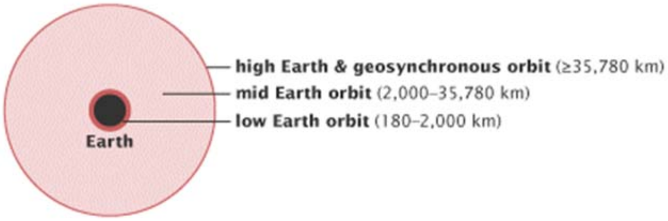

Figure 1. Orbital Regimes by Altitude

Source [1] R. Holli. (2009, Sept. 4). *Catalog of Earth satellite orbits.* [Online]. NASA. Available: http://earthobservatory.nasa.gov/Features/OrbitsCatalog/.

The focus of this paper is to quantify the risk to the human populace from the uncontrolled reentry of the Naval Postgraduate School's NPSAT1 spacecraft scheduled to launch on 15 September 2016. Designed to operate well within the LEO regime at 720 km above the earth, this spacecraft will provide a platform for space weather research as well as to demonstrate the ability of several experimental subsystems to perform on-orbit. Once the spacecraft has reached the end of its orbital lifetime, it will gradually reenter the earth's atmosphere, burning up in the process. Polices written by the U.S. Department of Defense (DOD) require the process of this reentry to be modeled so as to predict the risk, if any, there would be to the human population. In this paper, the governing policies behind this legislation are highlighted and required analyses are performed.

To solidify the concepts behind the various U.S. policies, the history of tracking artificial objects in space, sources and composition of orbital debris, and the concepts used by scientists to quantify risk are all addressed. Modeling programs, such as the National Aeronautics and Space Administration's (NASA) Debris Assessment Software (DAS) and Orbital Reentry Survival Analysis Tool (ORSAT), are also addressed in detail to provide the reader with an understanding of the mathematics involved and to highlight how their outputs determine a spacecraft's compliance with U.S. policy.

The results of the analyses performed for each component of NPSAT1 are reported in this thesis along with the context within which to interpret the data. Areas for continued research, technical recommendations, and relevant data used accompany a general discussion of the results in the last chapter.

II. ORBITAL DEBRIS

Orbital debris can be hazardous to operational spacecraft. The first collision between a satellite and an orbiting fragment of debris occurred in 1996 [2]. The Cerise, a 50-kilogram French satellite designed to provide intelligence on High Frequency (HF) communications leaving the Earth's atmosphere, was struck by a piece of an Ariane launch vehicle [2]. According to the National Space Science Data Center, the Cerise's six-meter long gravity boom was ripped off, leaving it unable to maintain its attitude. In order to prevent the total loss of the mission, engineers found a way to re-stabilize the spacecraft by re-designing the attitude control software to make use of Cerise's on-board electromagnets; saving the spacecraft and its mission [2]. The form of debris that struck the Cerise is not uncommon. Throughout the orbital regimes, there are several types of debris that pose risks to orbiting satellites; pieces of debris within the Low Earth Orbit may even pose risks to the Earth's population.

A. HISTORY OF U.S. SPACE SURVEILLANCE

An understanding of the kinds of debris and their locations is important. Three days before the launch of Sputnik I on 04 October 1957, the United States Navy finished the implementation of a space surveillance system that aimed to provide critical positioning information of orbiting satellites [3]. Originally designed to support the United States' Vanguard program, the system, dubbed "Minitrack," was named after its primary sensor system: an interferometer station that made use of a small oscillator [4]. The Minitrack system consisted of eleven internationally positioned optical, radar, and interferometer (Minitrack) stations located from San Diego to Havana, Cuba; each providing teletype information to the U.S. Navy on the positions of each detected satellites [4]. Minitrack's opening days were not without issue, however.

Engineers on the project understood that any artificial satellite launched into orbit would require the use of a transceiver system for data transmission and commanding. From this concept, the design of an interferometer-based space tracking system was born. In principle, these stations use the propagation of a signal transmitted from a satellite to determine tracking data from the direction of the spacecraft itself. Problems arose, however, when it was discovered that the newly launched Russian satellite communicated on a different frequency than the Vanguard spacecraft. Interferometer systems determine the target's direction through measuring the difference in phase between two antennas and thus tuning a system to operate on the correct frequency is critical. The U.S. Navy's Minitrack system, shown in Figure 2, was designed to operate at 108 Megahertz (MHz) while Sputnik I operated at both 20 MHz and 40 MHz [3]. Realizing that their system was effectively blind to the Russian satellite, U.S. Navy radio engineers outfitted each interferometer station with new oscillators and antennas to track the newly launched spacecraft; achieving results within just 1 day [3].

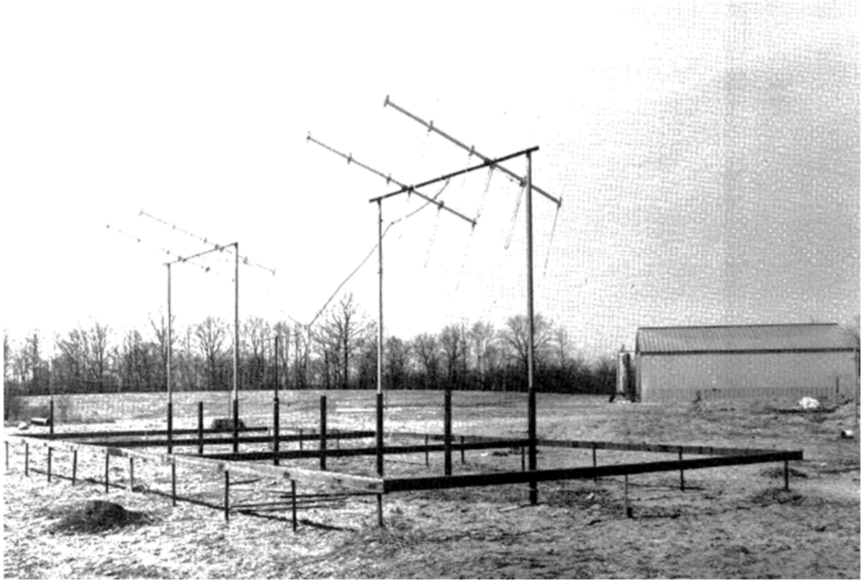

Figure 2. Minitrack Interferometer Antenna Station

Source [3]: W. R. Corliss, "Histories of the Space Tracking and Data Acquisition Network (STADAN), the Manned Space Flight Network (MSFN), and the NASA Communications Network (NASCOM)," NASA, Washington, DC. Tech. Rep. NASA-CR-140390, Jun. 1974.

Given the satellite's operation within the amateur radio band, a partnership was garnered between the Smithsonian Astrophysical Observatory (SAO) and the Naval Research Lab (NRL). The Smithsonian's effort, named "Operation Moonwatch," consisted of both scientists and hobbyists alike [3], all relaying Sputnik I's relative positioning data through the Smithsonian and ultimately into the Navy's Minitrack program. This partnership ultimately continued until 1975.

In a parallel effort, the U.S. Air Force developed a similar system named, Program 496L, or "Spacetrack" [5]. Consisting of nearly identical sensor systems the key advantages of this system over Minitrack was the number of cooperating sites and the ability to track passive satellites with greater accuracy. Ephemeris data gained from these stations were compiled by the U.S. Air Force and distributed via a bulletin that described the satellites' paths as they crossed the equator. When the redundancy of both systems was recognized, the stations for both Minitrack and Spacetrack were joined under the National Space Surveillance Control Center (NSSCC) in 1960; 3 years after the launch of Sputnik I [6].

One year later, the NSSCC was transferred to the North American Aerospace Defense Command (NORAD). By this time, the Minitrack program had evolved through iterative improvements and the program was renamed to "Space Surveillance," or SPASUR, and was still operated by the U.S. Navy. After developing the necessary infrastructure to merge the incoming data from both systems, NORAD named the combined system the "Space Detection and Tracking System" (SPADATS); subsequently, the NSSCC was then named the SPADATS Center [6].

B. MODERN U.S. SPACE SURVEILLANCE

Today, up to 29 stations [6] track and observe the presence of man-made objects orbiting the earth. Each station is part of a networked system of sensors called the Space Surveillance Network (SSN). The operation of this system was delegated by the U.S. Strategic Command (USSTRATCOM) to one of its

Component Commands, the Joint Functional Component Command for Space (JFCC-Space). Headquartered in Vandenberg Air Force Base, the JFCC, through the Joint Space Operations Center (JSpOC), reports that the SSN has catalogued over 39,000 man-made objects since the launch of Sputnik I and is currently tracking more than 16,000 objects on a daily basis. USSTRATCOM reports that of those 16,000 objects, only 5% of them have been classified as functional spacecraft. The remaining 95% of these objects have been classified as orbital debris [6].

Similar to the variations before it, the SSN incorporates a variety of sensor systems. Consisting of both conventional and phased-array radar systems, advanced electro-optical telescopes, and a satellite currently in orbit, the SSN is capable of making over 380,000 observations a day [6]; enabling the United States to maintain a database of each satellite in orbit. With locations ranging from an atoll in the Indian Ocean (Diego Garcia) to Thule, Greenland, the SSN provides operators with a global situational awareness capability. Although 29 stations participate in the activities of the SSN, many of them perform functions for other programs as well. With only 7 of the 29 stations being fully dedicated to the Space Surveillance Network, the system must use a predictive approach when tracking spacecraft [5].

When a spacecraft is launched, the Joint Space Operations Center predicts where that satellite will be and then tasks the SSN to search for the object [7]. Once a sensor discovers the satellite, the station performs measurements and observations on the spacecraft’s trajectory and then relays the information back to the JSpOC. From the information received from the SSN, the JSpOC estimates the orbital parameters of the spacecraft and uses that prediction as the baseline entry for the object. As the spacecraft orbits the earth, the SSN is tasked to search for it in the newly predicted location and update the spacecraft’s entry if there is a deviation from the calculated trajectory and the actual path [7]. This cycle repeats itself until the orbital parameters of the spacecraft have been accurately characterized; after which the SSN performs periodic searches for the object.

The entries generated from the process above are then collated into a large central database maintained by the JSpOC. This database, known as the “U.S. Space Catalog,” describes every man-made object that has orbited the earth since 1957. Each object in the catalog is represented by an individual entry composed of 25 elements [8]. These references are known by the community as two “Two Line Element” (TLE) sets; named for the way that data is organized within the entry itself.

TLE data is organized into three ultimate lines with the first line containing only one point of information: the object’s reference name. The second line contains the known or calculated mission parameters of the satellite (e.g., Epoch information, classification of the satellite, ephemeris type). The third line contains orbital information necessary for researchers to calculate the object’s position in space [9]. The TLE entry for NOAA 14, a weather satellite operated by the National Oceanic and Atmospheric Administration (NOAA), is provided in Table 1 as an example and an explanation of each data point is given in Appendix C. Various iterations of the TLE format have been implemented since its inception, each marked by the perturbation model used for calculations.

Table 1. Two Line Element (TLE) Entry for NOAA 14

```
NOAA 14
1 23455U 94089A   97320.90946019  .00000140  00000-0  10191-3 0  2621
2 23455  99.0090 272.6745 0008546 223.1686 136.8816 14.11711747148495
```

Source [9]: *NORAD NOAA elements.* (n.d.). CelesTrak. [Online]. Available: http://www.celestrak.com/NORAD/elements/noaa.txt.

As the SSN uses a predictive approach to track orbiting objects, the system must have the ability to accurately model spacecraft’s movement in space; accounting for both atmospheric drag and for the shape of the Earth [10]. The speed by which the Earth rotates causes the planet to stretch outward near the equator. The factor by which the planet stretches is known as oblateness. When oblateness is considered, the trajectories of the spacecraft are perturbed. To model the affects these perturbations have on the satellites orbiting Earth, NORAD produced a modeling algorithm known as the Simplified General Perturbation (SGP) model in 1960 [11]. This code, and the variants that followed, allow both NASA and DOD researchers to predict a spacecraft's position in orbit at any given time. To better aid spacecraft systems operating in LEO, the latest iteration of the TLE format makes use of SGP4 code (developed 10 years after SGP) to achieve a higher degree of positioning accuracy [11]. Even with this improvement, however, many spacefaring agencies have lamented [12] that the orbital positions calculated through the use of TLE information can lead to positioning errors in the magnitude of kilometers in LEO.

C. CONJUNCTION ANALYSIS AND COLLISION AVOIDANCE

With roughly 3,700 active satellites in orbit, assessing the likelihood of a collision each day between any two of these spacecraft, or with the remaining 12,900 catalogued items of space debris [13], is not trivial. It is to this end that conjunction analyses are performed when a close approach between two orbiting objects is expected. "Conjunction analysis" is the process of marrying the calculated locations of two satellites with the inherent uncertainties of their position data to predict the exact time of closest approach. As each calculation involves only the two satellites, or the one "pair," similar analyses must be made daily for nearly every single satellite on orbit. If it is determined that two satellites will pass by each other with an unacceptable clearance (defined by the ovoid shapes that result from the satellites position data and uncertainty), engineers and operators must make a determination as to what the next steps should be.

For a satellite traveling faster than 7.8 km/s, changing orbital trajectory is not a simple feat. Once it is determined that the trajectories of two satellites will pass as close as 1,000 meters from each other, the JSpOC produces a Conjunction Summary Message (CSM). These messages include such data as the time of closest approach, the estimated distance by which the two objects will pass, the passing speed of the object relative to the spacecraft, and the relative position and velocity of the object [14]. Satellite operators must then perform a series of analyses on the data to determine whether an avoidance maneuver is required. While the conjunction assessments leading to the generation of CSMs are performed 6 to 7 days in advance, operators are often only notified 3 days prior to the projected time of closest approach [15].

If the data contained within the CSM yields an unacceptable risk to the satellite program, the spacecraft operators may take an action known as a Collision Avoidance (COLA) maneuver. The decision to perform such a maneuver is often a complex process involving collating each reported conjunction event, quantifying the probability of collision, and then qualifying the risk to both the spacecraft and its mission [16]. If the probability of a collision is too great or the risk to the mission is deemed unacceptable, operators will program the spacecraft to perform a series of thrust maneuvers to avoid the oncoming satellite altogether. The reality of performing these analyses, however, is often further convoluted.

Accuracies of individual Conjunction Summary Messages are constrained through two elements: inaccuracies inherent to the TLE entries and the statistical methods used in determining the probability of a collision [17]. One of the key processes involved in performing a conjunction assessment is the determination of the probability of collision. To calculate this metric, it must be assumed that the distribution of uncertainty an object’s position in space is Gaussian by nature. Though sufficient for calculations with frequently updated TLEs, evidence has shown that conjunctions computed more than 3 days in advance induce an angular error of 5-degrees or more [17]. Considering the positioning and statistical errors associated with the use of CSM data, operators must also consider the possibility that changing the orbital trajectory of their spacecraft would result in yet another conjunction event; restarting the process.

D. CURRENT DEBRIS ENVIRONMENT

Orbital debris is comprised of three categories or types: non-operational satellites and rocket bodies, mission-related debris, and fragmented satellites [18]. Once a satellite becomes unresponsive, or non-operational, little can be done to correct its trajectory. Whether it is the result of a power failure, faulty propulsion system, or a processor fault, the spacecraft effectively becomes another piece of debris to be cataloged. Debris like this can be found in each orbital regime but its potential impact to operations in LEO is of great concern. As these spacecraft are typically unable to perform COLA maneuvers when necessary, collisions with these spacecraft—or any other object in space—could leave a devastating legacy.

On 10 February 2009 (16:56 ZULU), an Iridium communications satellite, Iridium 33, collided with a disabled Russian military satellite, "Космос-2251," above the Siberian Taymyr Peninsula [19]. Conjunction analyses estimated that the two satellites would pass each other by a half-kilometer. Though the magnitude of error within the CSM is not uncommon, the Iridium operators elected not to take action to avoid the collision or mitigate its probability. Approximately 770 km above the Earth, the two spacecraft collided at 10 km/s releasing over 1,500 fragments of trackable debris into the Low Earth Orbit [20] and an unknown quantity of debris too small to track. As of 2014, only 24% of the approximately currently cataloged 2,000 items of debris generated from the collision of these two spacecraft had reentered the Earth's atmosphere [21]; leaving the remaining 76% of fragments to be navigated by satellites operating in adjacent orbits.

Two years prior to the incident above, the People's Republic of China (PRC) launched their first successful Kinetic Kill Vehicle (KKV) on 11 January 2007 [22]. The KVV, a weapon designed to disable its target through the use of kinetic energy, impacted one of their own Fengyun-series weather satellites, FY-1C, in a test of the weapon's capabilities. The spacecraft was operating in a low-Earth polar orbit; an orbital trajectory favored by both weather and intelligence satellites. The PRC’s demonstration proved to the world they had the ability to target and successfully impact military reconnaissance satellites. The demonstration of their KVV program generated an additional 3,000 items of trackable debris into the LEO regime; more than any single event since the start of space exploration [22].

On 16 October 2012, the upper stage of an International Launch Services Proton Breeze M (Briz-M) rocket exploded with its two payloads still in tow. The rocket was supposed to transport two communications satellites, one Indonesian and the other Russian, into their intended Geostationary Orbits [23]. The rocket idled shortly after its launch on 06 August 2012 once one of its planned engine burns failed to ignite. Unable to burn off the remaining fuel, the spacecraft exploded 2 months later with more than half of its hydrazine and nitrogen tetroxide supply onboard. The explosion generated over 500 new items of debris into the Low Earth Orbit [23].

Though they are certainly the most dramatic events, system failures or collisions are not the only sources of orbital debris. The processes involved in the launch, deployment, and initialization of a satellite can each generate various forms of debris. Ranging from explosive bolts used in spring-release systems propelling spacecraft away from a rocket’s upper-stage, to the expulsion of lens caps, this type of debris is smaller in nature and strictly refuse. Assessing the risk presented by this category of debris is often difficult as modern tracking systems can only identify the larger items within this subset.

Comparatively small in dimension, collisions with these forms of debris can still result in mission failures. The standard formula for calculating the Kinetic Energy of an object has been solved in Equation 1 for an object with a diameter of 10 cm (the typical size of the smallest tracked objects [24]) traveling at a velocity of 7.8 km/s. Assuming the object’s mass is 20 grams, and that all of its energy will be transferred to the spacecraft at an orthogonal trajectory, the equation shows the energy released from the impact would be equivalent to that of an impact with a mid-size sedan traveling approximately 80.46 km/s, or 50 miles per hour.

$$KE = \frac{1}{2}mv^2 = \frac{1}{2}\left[20g\left(7800\,{}^{m}\!/_{s}\right)^2\right] = 608,400\,Joules \tag{1}$$

Equation 1: Kinetic Energy equation solved for specific values

E. KESSLER SYNDROME

Faced with the increased generation of debris, NASA scientist Donald Kessler described an event-driven concept for the future of orbital operations. In essence, after a collision between two objects occurs on-orbit, the debris from the collision will propel outward into adjacent orbits; increasing the probability of another collision. This trend will continue on an event-by-event timeline until the probability of a collision between two objects renders the orbit unusable. To that end, several U.S. policies have been enacted to take immediate steps in limiting the generation of additional debris; protecting future satellites and limiting the actuality of “Kessler’s Syndrome” [25].

Addressing both the potential for collisions and U.S. policy as a whole, satellite designers have employed a variety of debris mitigation schemes. Some of these schemes are active, utilizing on-board thrusters to reposition the spacecraft, while others are passive, sheltering the spacecraft with specialized shields designed to absorb hypervelocity impacts with debris. Other methods aim to reduce the risk of on-orbit explosions. The methods employ mechanisms to deplete the spacecraft of all stored forms of energy upon disposal and designing battery housings to capture fragments from a potential exploding battery cell. In the design of NPSAT1’s battery system, an aluminum housing encases the batteries [26]. This housing was then outfitted with a pressure relief valve and placed in-line with a filter to ensure that if an explosion did occur, it would be contained within NPSAT1. At the end of its mission, the battery system will be drained of all of its energy, an act known as passivation, to further prevent the possibility of an explosion [26].

F. ATMOSPHERIC REENTRY AND CONCEPTS

To determine which components of a satellite will ablate upon atmospheric reentry, researchers rely on specific formulas and modeling software to predict the failure of each component. In 1994 [27], scientists from both Lockheed Engineering & Services Company and NASA's Johnson Space Center proposed a way of modeling the risk of casualty from satellite reentry at a conference of the American Institute of Aeronautics and Astronautics (AIAA) seeking to quantify the survivability of spacecraft components reentering the Earth's atmosphere.

To model the risk to the world's population from reentering space debris, a formula can be used to relate the probability of impact, the possible locations of impact, the population density of that swath area, and sum of the cross-sectional areas of each object expected to impact the surface of the Earth. To be conservative, the authors opted to add an additional buffer of approximately 0.3 meters around the border of each object's calculated cross-sectional area. The resultant formula is shown in Equation 2 [27].

$$Expected\ Number\ of\ Causalities\left(E\right) = P\left(\frac{N}{A}\right)\cdot\left(\sum_{\#Objects}\left(0.6+\sqrt{A_{ref}}\right)^{2} m^{2}\right) \qquad (2)$$

$P = Probability\ of\ Impact\ for\ a\ Particular\ Region$

$N = Population\ Density\ in\ the\ Appropriate\ Latitude\ Band$

$A = Land\ Area\ in\ the\ Latitude\ Band \pm Orbital\ Inclination$

$A_{ref} = Cross\ Sectional\ Area\ of\ the\ Falling\ Object$

$NOTE:\ An\ additional\ 0.3 meter\ border\ is\ added\ to\ A_{ref}\ for\ buffer$

Equation 2: Expected Number of Casualties from Reentering Debris

The equation above requires the user to know each component's probability of impacting the Earth's surface, the cross-sectional area of each fragment, and the population density in the area of impact. The first two values can be obtained through software modeling and computer aided design (CAD) measurements. Beyond those data points, scientists must reference global population data, group the densities by latitude, and then account for the orbital inclination of the satellite; a factor that directly correlates to the flight path of the falling debris. Though several databases exist for global census and population data, achieving resolution for latitudinal population distributions 25 years in advance requires two different sources: the International Data Base (IDB) and the Gridded Population of the World (GPW). The IDB, a product of the U.S. Bureau of the Census, contains historical and current data for the global population while also estimating future growth [28]. The GPW spatially distributes populations with respect to latitude and longitude [28]. Both databases are necessary when estimating the impact area of fallen debris at the spacecraft's end-of-life.

When considering the beginning stages of spacecraft design, the risk presented in Equation 2 can be quantitatively understood before an analysis is performed. If a researcher were to assume that each component they were designing failed to ablate after reentering the Earth's atmosphere, a highly conservative risk assessment could be made. Considering the design of NPSAT1, if two objects were thought to have the ability to survive reentry, Equation 2 could be solved to provide an initial risk assessment. Equation 3 [27] solves Equation 2 [27] under the assumption that the reentering components have cross-sectional areas of 0.016 m2 and 0.00108 m2, respectively; both items falling into the same densely populated with identical impact areas (all assumed values are shown in Equation 3):

$$Expected\ Number\,of\ Causalities\left(E\right)=P\left(\frac{N}{A}\right)\cdot\left(\sum_{\#Objects}\left(0.6+\sqrt{A_{ref}}\right)^{2}m^{2}\right) \tag{3}$$

$$E=0.6\left(\frac{32,375,525\,people}{2.4\cdot 10^{11}\,m^{2}}\right)\cdot\left(\left(0.6+\sqrt{0.016m^{2}}\right)^{2}+\left(0.6+\sqrt{0.00108m^{2}}\right)^{2}\right)$$

$$E=5.9955\cdot 10^{-5}\,persons$$

Equation 3: Expected Number of Casualties (Solved)

Due to the linearity of the equation, relationships between the expected number of casualties and each of the variables can be understood. For instance, if the predicted land mass to be impacted is larger, it becomes less and less likely that a casualty will occur. If that area were to contain a significant populous density, then the expected number of casualties will increase. In both cases, it can also be realized that the mass of the reentering object serves to amplify its impact as well as increase the risk of injury to the people living down below.

The risk to human life posed by spacecraft and debris reentering the Earth’s atmosphere needs to be fully understood before a program can launch into orbit. To this end, numerous government organizations have developed offices, standards, and supporting resources for satellite designers to rely on and adhere to.

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III. U.S. POLICY ON ATMOSPHERIC REENTRY AND DEBRIS

The Joint Functional Component Command for Space (JFCC Space), a component of USSTRATCOM, continues to catalog new objects on a daily basis. With the number and density of orbital debris increasing, spacefaring agencies across the world, both civil and military, have implemented regulations and procedures to address the generation of even more debris. Since the inception of the Kessler Syndrome, debris mitigation has increasingly become a relevant topic and design constraint for the modern spacecraft. This relevancy is further emboldened when considering the debris reentering the Earth's atmosphere. The following subchapters of this paper highlight three avenues of U.S. administrative policies regarding the commercial, civil, and defensive use of space; each combining to illustrate the commitment of the United States to the mitigation of orbital debris and human safety.

A. COMMERCIAL POLICIES

The combination of both the Commercial Space Launch Act (Public Law 98–575) of 1984 and the Commercial Space Act (Public Law 105–303) of 1998 designated the U.S. Department of Transportation (DOT) as the responsible federal agency for both the enablement and regulation of commercial space launches and reentries [29]. Currently, the DOT further delegates this function to the Federal Aviation Administration's (FAA) Office of Commercial Space Transportation, endowing the agency with the responsibility of regulating any commercial space transportation activity conducted within the United States or by a U.S. citizen [29].

Through the regulation of 238 launches since 1989 [30], the FAA developed its own criteria for the safe reentry of commercial vehicles. Whether or not the rocket body or spacecraft was designed for reusability, the FAA lays out the same stipulations as to the safety measures required for commercial programs to operate in space. These requirements, along with laws governing the entire U.S. government, are detailed in Chapter 3 of the Title 14 Code of Federal Regulations (CFR) [31].

One such commercial entity governed by this document is SpaceX. The design of the company's Falcon Heavy rocket, the same launch vehicle chosen for the NPSAT1 satellite, chooses to return the first stage of the rocket back to its originating launch pad for reuse. Among the numerous safety requirements that are levied upon SpaceX by the CFR and FAA, the most applicable regulation to the context of this paper involves the return of its first stage and its potential risk to the human population along its return path. In summary of the requirement quoted below, the stage's reentry should neither pose a probability of casualty greater than 1:10,000 to any one human, nor pose a greater than 30:10,000 probability of casualty to the public as a whole [31].

> (i) For public risk, the risk level to the collective members of the public exposed to vehicle or vehicle debris impact hazards associated with a proposed mission does not exceed an expected average number of 0.00003 casualties per mission (or Ec [casualty expectation] criterion of 30×10^{-6}) to members of the public from the applicant's proposed activity; and
>
> (ii) For public risk, the risk level to an individual does not exceed .000001 per mission (or individual risk criterion of 1×10^{-6}). [31]

B. CIVIL POLICIES

Arguably the most recognized authority in space exploration, the civilian National Aeronautics and Space Administration has been a leading voice in mitigation of orbital debris and space safety. Taking the international lead in this effort, NASA created the Orbital Debris Program Office (ODPO). Operating from NASA's Johnson Space Center, this office is the primary organization responsible for both assessing and mitigating the threat posed by orbital debris.

To that end, the ODPO authored three documents by which NASA spacecraft programs should adhere to: NASA Standard (NASA-STD) 8719.14A, Procedural Requirement (NPR) 8715.6A, and Handbook (NHBK) 8719.14. The current revisions, authored on 8 December 2011, 14 May 2009, and 30 July 2008, respectively, combine to set in place both laws and best practices for program managers and engineers alike to protect spacecraft from and limit the generation of orbital debris.

NASA Standard 8719.14A, Process for Limiting Orbital Debris, establishes a multitude of requirements aimed at the reduction of generated debris, modeling the probability of collisions (both known and unknown), and modeling the risk that reentering debris will pose to the human population below. This document has become a required set of design, planning, and execution requirements for all NASA programs through the adoption of NPR-8715.6A [32]. Beyond mandating that any and all space-destined programs strictly adhere to the requirements set forth in NASA-STD-8719.14A, this document also provides information on the data required to satisfy each requirement and the timeframes by which technical, programmatic, and mission data should be disseminated.

To help designers navigate through these requirements, NASA authored handbook 8719.14, the Handbook for Limiting Orbital Debris. Intended to both educate and enable engineers and program managers, NHBK 8719.14 provides background on the history of orbital debris mitigation and its impact through useful figures and data analyses collected across multiple missions. Specifically referenced in this document are two software programs: the Debris Assessment Software (DAS) and the Orbital Reentry Survival Analysis Tool (ORSAT) [5]. These two programs, discussed in a later subchapter, are the only recognized modeling programs for determining a program’s compliance with particular technical requirements within NASA-STD-8719.14A [5]. DAS provides its users with the ability to input mission and design data into the program and confirm their spacecraft’s compliance with ten different requirements called out within the NASA standard. The compliance with each of these requirements, ranging from predicting the probability of an accidental collision with another object (Requirement 4.5–1) to the determination of which components will survive reentry (Requirement 4.7–1) [32], are reported back to the user through a

Boolean indicator within the GUI. ORSAT focuses more specifically on the modeling of reentering spacecraft and component survivability.

C. MILITARY POLICIES

Responding to the President of the United States' growing concern [33] of the impact posed by orbital debris, the U.S. Department of Defense released their own instruction set similar to NASA's Procedural Requirement 8715.6A and Standard 8719.14A. Department of Defense Instruction (DODI) 3100.12, titled Space Support, implements policies and guidelines for operating military space programs and assigns roles and responsibilities to several agencies. Specifically, the DODI assigns the responsibility of transporting, launching, operating both rockets and spacecraft to the U.S. Air Force.

The U.S. Air Force, now acting as the military's executive agent for space operations, published their own instruction set, known as an Air Force Instruction (AFI), to augment the directives set by the Department of Defense. Entitled the Space Safety and Mishap Prevention Program, Air Force Instruction 91–217 itemizes the specific requirements military programs should comply with [24]. NPSAT1, as a DOD satellite is subject to both of these instructions.

Among the requirements levied upon military spacecraft, two outputs are required to demonstrate a program's compliance with debris mitigation: a Space Debris Assessment Report (SDAR) and the End-of-Life Plan (ELOP) [24]. The current revision of the AFI (11 April 2014) combines both of these documents into one report, hereafter referred to as the "SDAR/EOLP," which spacecraft programs must submit before critical launch milestones—namely, before both the Preliminary and Critical Design Reviews and before the Flight Readiness Review. Though this document requires spacecraft programs to provide a vast amount of information about their design, the successful completion of the SDAR/EOLP requires these designers to perform several analyses to demonstrate that their program is in full compliance with both AFI 91–217 and DODI 3100.12.

NASA’s standards and the DOD’s instructions were born from a response to the same mandate, Presidential Directive 49: National Space Policy [32], [33]. In 1996, President Clinton declared that the U.S. government, to include both the DOD and NASA, will actively seek to minimize the generation of orbital debris and take a lead international role in the development of mitigation polices. From this directive, the U.S. government Orbital Debris Mitigation Standard Practices (ODMSP) was established. Relatively small in length at only three pages, the ODSMP established that every U.S. spacefaring program must plan for and assess the risk of orbital debris in four major areas: the intentional release of debris, accidental explosions, orbital flight paths, and post-mission disposal [34].

As mitigation practices and policies matured, the instruction sets of each agency became increasingly similar. With the exceptions of administrative and operational differences, the requirements specific to mitigating orbital debris are functionally identical between the DOD and NASA. In regard to the reentry of NPSAT1, two excerpts are given below; one from AFI 91–217 and the other NASA-STD-8719.14A. Both requirements address the probability of casualty to human life from reentering debris.

> The collective risk to the general public due to uncontrolled atmospheric reentry shall not exceed a casualty expectation (Ec) of 100×10^{-6} (one hundred in one million). Requirement 5.7.3.1.1.1 of [24]
>
> a. For uncontrolled reentry, the risk of human casualty from surviving debris shall not exceed 0.0001 (1:10,000). Requirement 4.7–1 (4.7.2.1) of [32]

Both requirements state identical limitations for the acceptable level of risk reentering spacecraft can pose to humanity. Though particularly beneficial for safety, the harmonizing of these critical requirements can prove beneficial to mission planners and developers. Uniformity between these documents on the matter of orbital debris allows both DOD and NASA engineers to use DAS as a compliance analysis tool. This ability saves overall program cost, resources, and limits the possibility of human error. While DAS does not reference U.S. Air Force requirements, the combined SDAR/EOLP requires military programs to use DAS as an analytics tool to verify the compliance of several requirements stipulated throughout AFI 91–217. For reference, a comparison of the requirements able to be satisfied through DAS for both documents has been provided in Appendix D.

D. ATMOSPHERIC REENTRY MODELING

Originally developed in 1998, NASA's Debris Assessment Software [35] was designed to provide program managers and engineers with a quick and conservative assessment tool [36]. In the latest revision, version 2.0.2, DAS enables the user to verify the design of their spacecraft along ten different requirements specified within NASA Standard 8719.14A http://orbitaldebris.jsc.nasa.gov/mitigate/das.html. Either through the import of a comma-separated-value (CSV) file or through manual input, operators of the software can account for each component of the spacecraft's mass, material properties, size, and relative shape [36]. These components can be organized either as a hierarchical, nested, design or as individual pieces.

DAS functions as a component- or object-oriented analysis program in that the program considers the reentry of each individual piece of the spacecraft rather than the spacecraft's reentry as a whole. Several technical assumptions must be taken into account when using a component-oriented program such as DAS. If the satellite is no longer considered to be whole, then an initial break-up altitude must be assumed by which each detailed component will be introduced into the Earth's atmosphere for reentry. As the majority of spacecraft reentering the atmosphere begin to decay around 72 to 84 km above the surface, DAS assumes this initial breakup altitude to be the mean of this range, 78 km. In addition to assuming an initial altitude, the software also assumes that each detailed piece of the reentering satellite behaves as a standalone component.

As a spacecraft reenters the Earth's atmosphere, it is introduced to a great amount of heat. Aerodynamic drag heats the outer aluminum sheath to a point at which it begins to ablate. It is well understood that as the outer metal housing is heated, it will then transfer that energy in the form of radiated heat and energy to neighboring components. Thus the inner components of the spacecraft have already been exposed to significant heat before they are physically exposed to the Earth's atmosphere. DAS assumes that while the spacecraft undergoes this process, the heat generated from reentry is not transferred between parent and child components. In fact, once a parent structure ablates, its child components are exposed to an assumed atmosphere of 300 Kelvin; approximately 80 degrees-Fahrenheit. This approach illustrates the conservative nature of DAS.

DAS' conservative logic can lead to "false positives," suggesting that certain components will fall to the Earth's surface when they would actually ablate upon reentry. This conservatism is helpful though when considering that DAS is programmed to confirm the compliance of each spacecraft with ten different NASA requirements. Confirming that the probability of collision with objects on-orbit is within required limits, that there is less than a 1:10,000 chance of a spacecraft causing a fatality upon reentry, and assessing the impact that any mission-related debris would cause within the LEO orbit are all calculations that can be made; the output of each yielding whether their program is compliant or not. It is for this reason that DAS' conservative approach is valuable: if a program were to be found compliant through DAS, no further analysis would be necessary. Thus DAS ultimately could save time and mission resources throughout the design process.

If a program's spacecraft were to fail, further analysis would need to occur in a program capable of higher fidelity results. NASA's Object Reentry Survival Analysis Tool is the organization's primary resource in the realistic prediction of a spacecraft's ability to survive the reentry process; albeit a spacecraft or launch vehicle. Unlike DAS, this tool aims to tackle only the requirement pertaining to atmospheric reentry laid out by NASA Standard 8719.14A [22].

ORSAT makes use of a variety of models (trajectory, thermal, atmospheric, aerodynamic, and aerothermodynamic) to compute the risk of impact. The program also accounts for material's properties changing with respect to temperature; allowing researchers to model reentering components as either a lumped mass (equivalent to DAS) or with heat conduction. DAS is often preferred to ORSAT as an initial tool as it is publically available and can be operated with a minimal amount of training.

Whether entering data into DAS or ORSAT, components can only be represented as one of four shapes: a flat plate, a box, a cylinder, or a sphere. For equipment and components that do not resemble one of these four geometries, an equivalent structure must be created within the program. These structures must exhibit the same thermal mass, appropriate dimension according to both the weight and density of the material, and resemble one of the allowable shapes. Once every component of the spacecraft has been correctly accounted for within either program, the analysis can be performed.

IV. SPACECRAFT OVERVIEW

The NPSAT1 satellite, illustrated in Figure 3, was developed by the Naval Postgraduate School (NPS) to provide a platform for both higher education of officers and a testbed for experimental payloads. The education of military officers within the Space Systems Operations and Space Systems Engineering curricula is accomplished through the design, building, testing and evaluation of each sub-system. This level of testing directly translates to quality platforms by which the various experiments on-board can be evaluated for further research. Once on orbit, NPSAT1 will provide operators with information on the space weather as well as provide data to aid research in ionospheric physics [26].

A. PHYSICAL DESCRIPTION AND LAUNCH PARAMETERS

NPSAT1 will launch from Cape Canaveral Air Force Station (CCAFS) to an operational altitude of 720 km [26]. The one-meter tall cylindrical dodecagon will make use of two experiments furnished by the Naval Research Laboratory and will also house several experiments designed by NPS to demonstrate the flight-readiness of their respective technologies. Weighing 82 kg, Table 2 classified NPSAT1 as a microsatellite [32] and, given its dimensions, is allowed to be launched from a specialized payload adapter developed by the Space Test Program (STP). This adapter acts as a multi-vehicle transport system; being able to launch multiple smaller satellites in parallel with the launch vehicle’s main payload. As the rocket booster propels its primary spacecraft into orbit, this adapter ring would allow NPSAT1 to be ejected into an orbital inclination of 24 degrees once at altitude.

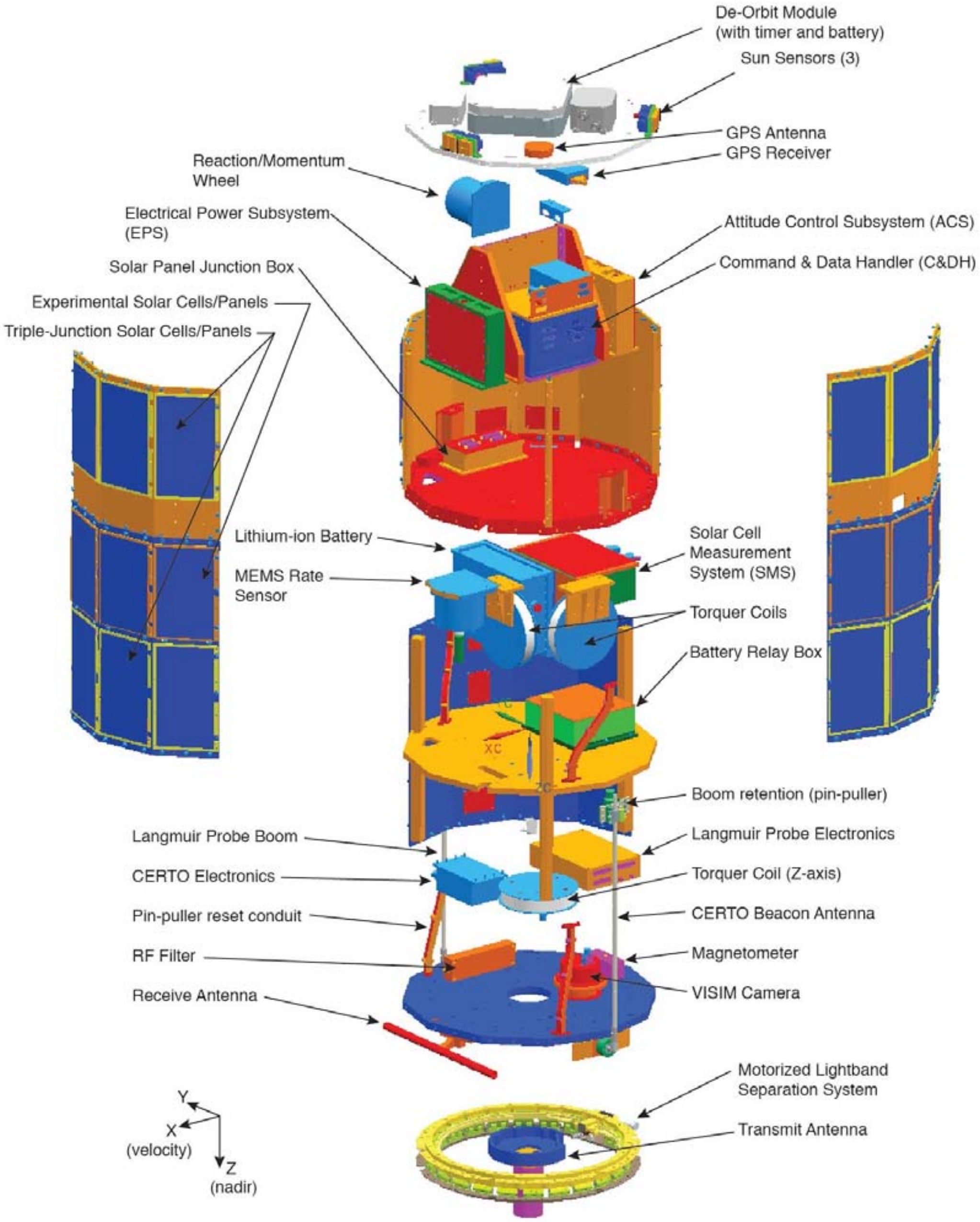

Figure 3. Expanded View of NPSAT1

Source: This image was provided courtesy of Daniel Sakoda of the Space Systems Academic Group of the Naval Postgraduate School.

Table 2. Small Satellite Categories by Wet Mass

Satellite Class	Qualifying Wet Mass (kg)
Minisatellite	100 kg to 500 kg
Microsatellite	10 kg to 100 kg
Nanosatellite	1 kg to 10 kg
Picosatellite	0.1 kg to 1 kg

Source [32]: Process for Limiting Orbital Debris, NASA Standard 8719.14A, 2008.

B. COMMAND AND DATA HANDLING SUBSYSTEM

The spacecraft's ability to process commands, manage the flow of data between subsystems, and provide for data storage functionality lies within the Command and Data Handling (C&DH) subsystem. The CD&H is comprised of several printed circuit boards (PCB) stacked on top of each other; each having a common interface between them. The operating system for this subsystem was developed in Linux given the platforms flexibility, support for multitasking, and comes freely available.

C. ELECTRICAL POWER SUBSYSTEM

While on orbit, NPSAT1 will be powered by 36 solar panels covering the twelve aluminum sides of the spacecraft. Each side houses three solar panels each: two commercially available solar panels and a one experimental solar panel. Each of these panels are made up of triple-junction solar cells, providing enough energy to charge 49 lithium-ion cells that make up the NPSAT1 battery. The battery is configured with seven lithium-ion cells in series and seven strings of these cells in parallel; providing the spacecraft with 225 Watt-Hours [26] of energy storage. Each of the series strings of cells has a current sensor that allows spacecraft operators to monitor the battery use from downloaded telemetry.

D. ATTITUDE AND CONTROL SUBSYSTEM

For attitude control while on-orbit, NPSAT1 makes use of three magnetic torquer coils, or air coil wires. Torquer coils are windings of copper wire, designed in such a way to behave as magnets. NPSAT1's torquer coils have been implemented to leverage the magnetic field of the Earth to orient the spacecraft while on orbit. These coils, combined with a magnetometer, and a controller, make up the spacecraft's Attitude Control Subsystem (ACS). As the spacecraft orbits the Earth, the ACS will measure the readings from the magnetometer. The spacecraft command and data handler (CDH) runs the attitude control algorithm, using the spacecraft's location and a look-up table of the Earth's magnetic field to determine a preferred magnetic field vector. It then compares the preferred magnetic field vector with that measured by the magnetometer to determine its pointing error. The CDH then commands the ACS controller to align these two values by varying current to the torquer coils; using magnetic control to position the spacecraft to within ±10° of the correct orientation.

E. RADIO FREQUENCY SUBSYSTEM

The Radio Frequency Subsystem (RFS) allows for data transmissions at UHF 450 MHz for uplink, and S-band 2279 MHz. These uplink and downlink channels, respectively, provide full-duplex communication through nadir-pointing antennas. The RFS can relay the spacecraft's sensor and performance data to ground stations located in Ohio, Utah, California, and Hawaii.

To command the spacecraft while in orbit and retrieve subsystem information, NPSAT1 will leverage the Mobile CubeSat Command and Control (MC3) [37] network of ground stations. Developed to support the National Reconnaissance Office's Colony program, the MC3's network of ground stations make use of both UHF and S-Band telemetry systems to command over 30 experimental spacecraft as they orbit and retrieve data. NPSAT1 operators will leverage the MC3's architecture to remotely command the spacecraft and provide a portal by which researchers and users can access experiment data across a secure web server.

F. SPACECRAFT END OF LIFE

U.S. regulations require that the NPSAT1 spacecraft be disposed of, either purposefully or naturally, no more than 25 years after its end of life [33]. Since the spacecraft will be launched into the LEO regime, both AFI 91–217 and DODI 3100.12 require NPSAT1 to reenter the Earth's atmosphere; incinerating the spacecraft in the process. To satisfy this requirement, NPSAT1 will automatically deploy a NanoSat Terminator Tape (NSTT) 18 months after it separates from its launch vehicle. Once deployed, the deorbiting mechanism developed by Tethers Unlimited, Inc., will create enough aerodynamic drag to slow the satellite's speed while on orbit. This loss in speed will ultimately alter the spacecraft's trajectory in such a way that it reenters the Earth's upper atmosphere, where it will be exposed to an increasing amount of drag. Throughout this process, the spacecraft will be exposed to enough drag to heat each component in such a way that NPSAT1 eventually will be incinerated.

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V. REENTRY ANALYSIS AND RESULTS

When calculating the potential for human casualties, DAS predicts the altitude of demise for each object based upon the material's density, cross-sectional area, and aerodynamic (thermal) mass. Once this analysis is complete, the results are then compared to the Requirement 4.7–1 within NASA Standard 8719.14A. Any object that falls to Earth is then further analyzed to determine the energy by which it strikes and the expected number of human casualties as a result. If an item of debris is predicted to have greater than a 1:10,000 [24] chance of surviving the reentry process with an impacting energy of 15 joules or more [32], the spacecraft is deemed to be non-compliant by AFI 91–217 standards. The operational concept of using the DAS program is that particular components that were determined to fail within the program's logic require further analysis within the ORSAT software.

A. TECHNICAL ASSUMPTIONS

The DAS software already contains several conservative values for the densities of commonly used materials such as Aluminum and Steel. In order to account for less common materials, the user is required to manually input the relevant data from their respective datasheets. The material density used for each of the materials involved in the design of NPSAT1 is described in Table 3, with the pre-existing values stored within DAS denoted in gray.

Table 3. NPSAT1 Material Properties Modeled within DAS

Material Name	**Density (kg/m^3)**
Polycarbonate (aka Lexan)	1250 [35]
Delrin (Polyoxymethylene)	1420 [38]
Viton A	1900 [39]
Rulon J	1950 [40]
Aluminum 6061-T6	2707 [35]
GaAs	5316 [35]
Steel AISI 304	7900 [35]
Copper Alloy	8938 [35]

DAS operates under the assumption that once a parent structure ablates, the subcomponents are then exposed to the elements without prior bias (e.g., thermal transfer from the super-heating of its surrounding structures). Naturally, this is a more conservative approach, as the innards of a sub-assembly would be exposed to heat from the ablation of the structure surrounding it; thus the altitude of demise for child objects is inherently lower. Navigating DAS' peculiarities proved to be a significant effort so it is recommended that any attempt to replicate the work performed in this thesis should make use of the input data provided in Appendix A.

B. ANALYSIS RESULTS

To conservatively model the reentry of NPSAT1, 707 different components across 84 assemblies and sub-assemblies were measured with CAD software. After being categorized by mass, material, and geometry, like components were then grouped to satisfy DAS' 200 component limit [36]. The resultant data was organized into a single-level hierarchy to evaluate the reentry sequence of NPSAT1.

Once the data had been collated and reformatted for entry into DAS, the individual spacecraft components were run through the DAS reentry algorithms. Understanding that conservative geometries were applied to a significant portion of the satellite's components, the first several iterations of the software would yield different component failures that were then further scrutinized to improve the geometric equivalence; taking into account both the overall dimensionality and relative shape of the original components. A dodecagonal plate, for example, could be entered into DAS as either a cylinder or as a flat rectangular plate. Entering that shape as a flat plate large enough to encompass the original component would be the most conservative approach. If this conservatism resulted in a failure, the geometry would be further reduced to either a cylinder or a flat plate as DAS allowed. In either case, the equivalent geometries would have identical surface areas, volume, and relative shape. The results of this analysis conservatively indicate that while 19 overall fragments from NPSAT1 may survive reentry, the sum probability of casualties resultant from these fragments satisfies the requirements established in both AFI 91–217 and DODI 3100.12. Results from the analysis are illustrated in Figure 4.

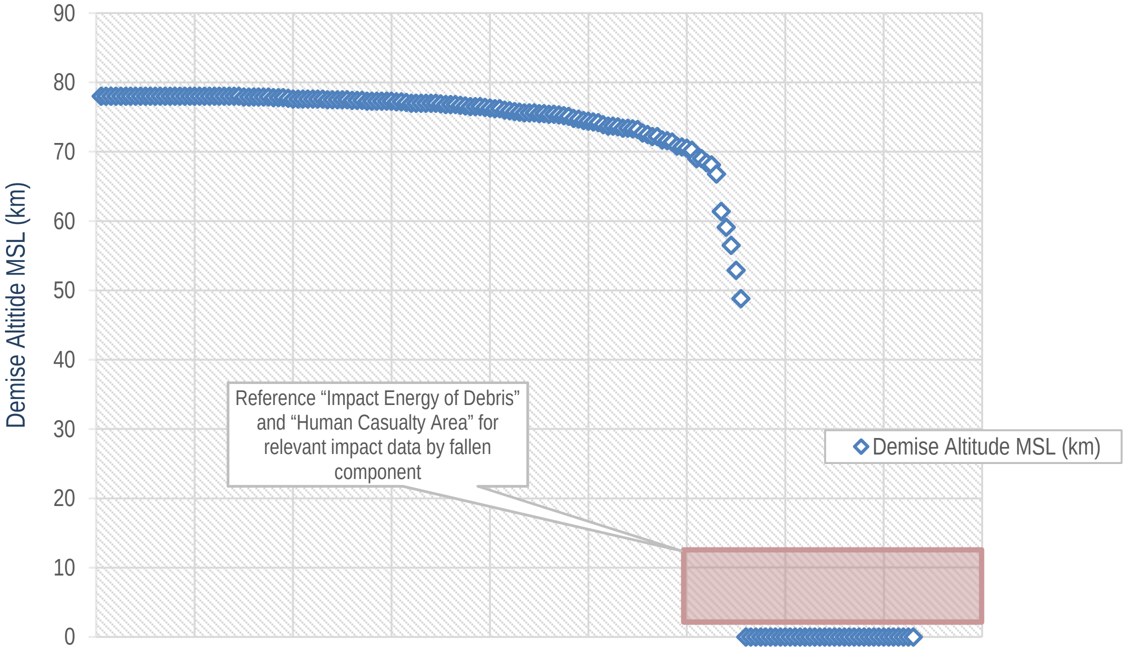

Figure 4. Demise Altitude (MSL) of Debris by Component

Figure 4 shows a linearly-scaled depiction of the demise altitude for each component within the NPSAT1 spacecraft relative to mean-sea-level (MSL). The data shown was sorted to illustrate the demise altitude in a descending pattern with each data point along the horizontal axis representing a specific component rather than a unit of time. The 19 components that fail to ablate upon reentry (highlighted in red) each strike the Earth with varying energies and predicted impact areas. Those components are highlighted in Figure 5.

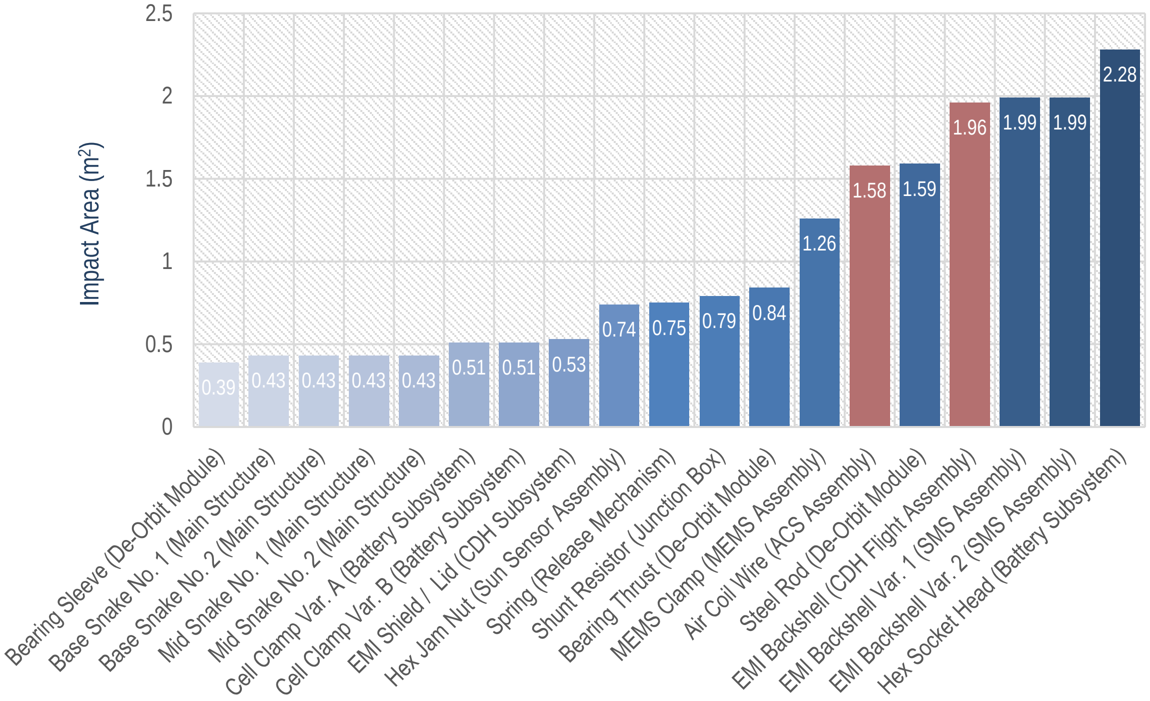

Figure 5. Predicted Impact Area of Debris by Component (m^2)

Each component that survived the reentry process, hereafter referred to as debris, will strike the surface of the Earth within a certain radius, or square-area. Figure 5 enumerates the expected area of impact, per component, predicted by DAS. For each item of debris that survives atmospheric reentry, the item’s impact energy must be taken into account alongside its projected area of impact. When considering the reentry criteria for spacecraft debris set by AFI 91–217, only two components exceeded 15 joules of energy; the force required to cause a human fatality. Figure 6 illustrates the calculated impact energy for each item of debris while specifically highlighting the two spacecraft components that would exceed an impacting energy greater or equal to 15 Joules.

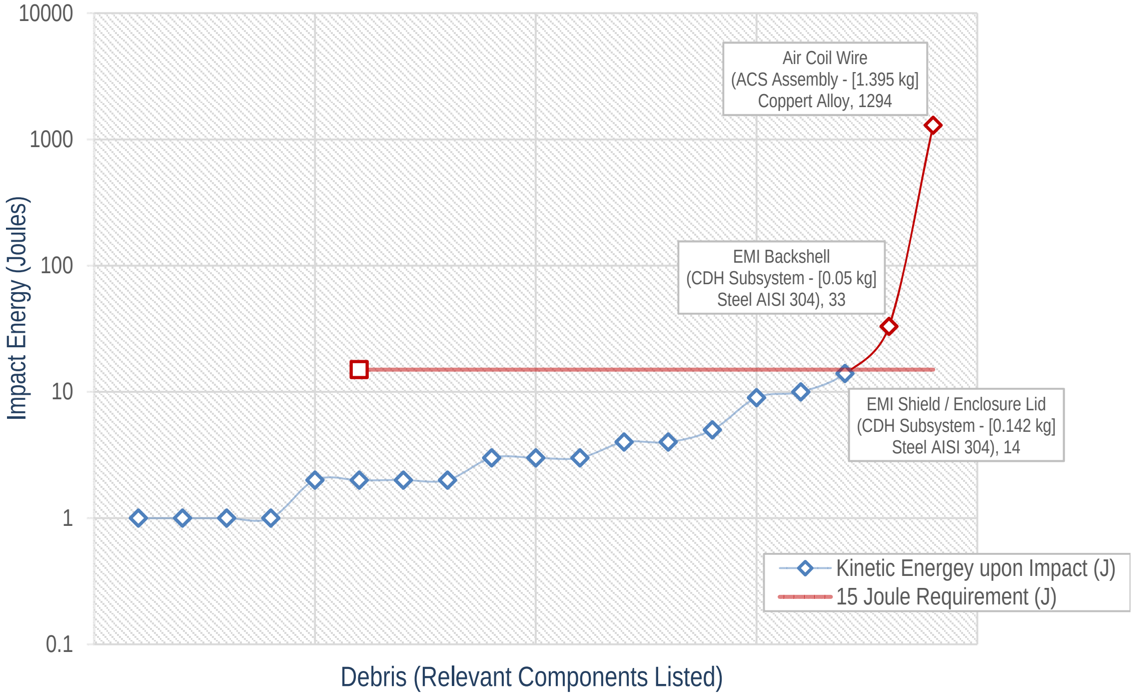

Figure 6. Predicted Energy (J) of Impact by Component

Logarithmically scaled, Figure 6 depicts the Kinetic Energy (or Impact Energy) transferred by each object that survived the reentry process. Three values are highlighted to draw attention to their significance: an Electromagnetic Interference (EMI) Enclosure Lid, a few steel backshells belonging to cables that attach to the overall EMI enclosure, and two air coil wires contained within the ACS assembly. The EMI enclosure exhibits only 14 Joules on impact, placing the component just below the 15 joule requirement. The other components highlighted exhibit 33 Joules and 1294 Joules, respectively. Given the calculated probability of a human fatality being 1:14,500, NPSAT1 is fully compliant with both AFI 91–217 and DODI 3100.12 requirements for a spacecraft undergoing atmospheric disposal or reentry.

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VI. CONCLUSIONS AND RECOMMENDATIONS

A. ATMOSPHERIC REENTRY OF NPSAT1

Standing under a meter tall and weighing only 90 kg (originally predicted to be 82 kg), the initial expectation was that each of the spacecraft's components would ablate upon atmospheric reentry. On the contrary, 19 of the 707 different pieces composing NPSAT1 failed to ablate during the reentry process. Upon inspection, only two of these components yielded an energy and impact area great enough to warrant review: the copper air coil wires designed into the Attitude Control Subsystem (ACS) and several cable backshells implemented to help protect the spacecraft from electromagnetic interference (EMI).

The ACS assembly's air coil wires (seen in Figure 7), or torquer coils, use the magnetic field emanated from the Earth to point the spacecraft toward Earth. Each of the three 1.395 kg air coil wires on NPSAT1 consist 37 layers of wrapped copper wire, resembling a large solenoid. Between their core and insulations, these wires are approximately 0.370 millimeter in diameter and are wrapped around the housing 68 times, or turns, per layer. To model this component's reentry into the Earth's atmosphere using DAS, the operator must either reduce the structure to a simple cylinder or a flat plate of strewn wire; each introducing a significant amount of error. Though DAS predicts that these coiled wires will survive reentry, it is more probable that these copper wires will unwind during the reentry process as their insulation is melted. This action would expose the wires to significantly greater stress during atmospheric reentry and would most likely end in their complete ablation. It should be noted that neither the air coil wire's housing (Figure 7) nor their electrical connections were predicted to survive reentry within DAS.

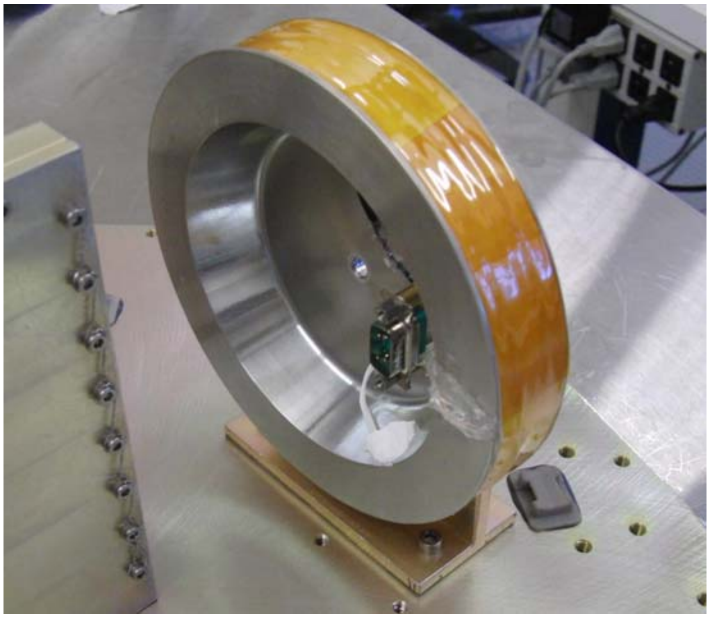

Figure 7. Picture of the Integrated Air Coil Wire (ACS Assembly)

Source: This image was provided courtesy of Daniel Sakoda of the Space Systems Academic Group of the Naval Postgraduate School.

The other component that was predicted to survive reentry are the EMI backshells directly connected to the Command and Data Handler (CDH). These EMI backshells (illustrated in Figure 8), are made of thin stainless steel to prevent electromagnetic energy from entering or exiting the cable; interfering with sensor and data readings. The prediction of these components surviving reentry with a kinetic energy exceeding 15 J was surprising as they have a thermal mass of 0.05 kg. These backshells are milled from a solid piece of metal to create a hollow void for cables when assembled. Modeling this component requires the operator to reduce the overall structure to either a box or to a flat plate by which all of the sides have been flattened outward.

Figure 8. Picture of the EMI Backshell (CDH Flight Assembly)

Source: This image was provided courtesy of Daniel Sakoda of the Space Systems Academic Group of the Naval Postgraduate School.

Addressing the risk of any component surviving atmospheric reentry requires both practicality and conservative modeling. When considering the circumstances by which these components will reenter, it is apparent that the predictions given by DAS are highly conservative in nature. Though 19 pieces of NPSAT1 were ultimately predicted to survive, DAS calculated that the risk to human casualty from an uncontrolled reentry was 1:14,500, clearly compliant with Requirement 5.7.3.1.1.1 of AFI 91–217 and Requirement 6.4.1 of DODI 3100.12.

B. SUMMARY AND FUTURE RESEARCH

Only 5% of the objects currently being tracked in space are operational spacecraft. With each new launch, the probability of a spacecraft colliding with nearby orbital debris increases. Besides the risk to the mission itself, a collision between fragmented debris, expended rocket body, or orbiting spacecraft could result in the generation of thousands more items of debris. The U.S. requirement to dispose of non-operational spacecraft, either through atmospheric reentry or through a disposal orbit, helps to mitigate this risk. For spacecraft reentering the Earth’s atmosphere, additional modeling needs to be performed to ensure the safety of the human population below.

Though NPSAT1 is in full compliance with U.S. regulations governing reentering spacecraft, this paper identifies two areas for further research. Given that the primary mission of NPSAT1 is educate students, comparing the modeled reentry of the two components highlighted in this paper with predictions made in ORSAT would aid the Space Systems Academic Group in understanding the true demise altitudes of these components. Additionally, an analysis of whether DAS, given its conservative nature and limitations, is an effective tool for predicting the atmospheric reentry of microsatellites would help the space community at large

APPENDIX A. DAS REENTRY INPUT FILE

The following table contains the information necessary to replicate the work performed in this paper. Appropriately formatted and grouped, the contents of this file can be stored as a comma-separated-value (CSV) file that can be imported into NASA's Debris Assessment Software (DAS). One of the principle limitations of the DAS program is the number of components allowed to comprise the spacecraft. To reduce the 707 components that constitute NPSAT1, like components were grouped and then further categorized by composition, geometry, and thermal mass. Though DAS does not require the input file to have a particular name, Table 2 must be saved as a separate CSV file titled, "matprop.csv," in the project's root folder to make use of the data in Table 4.

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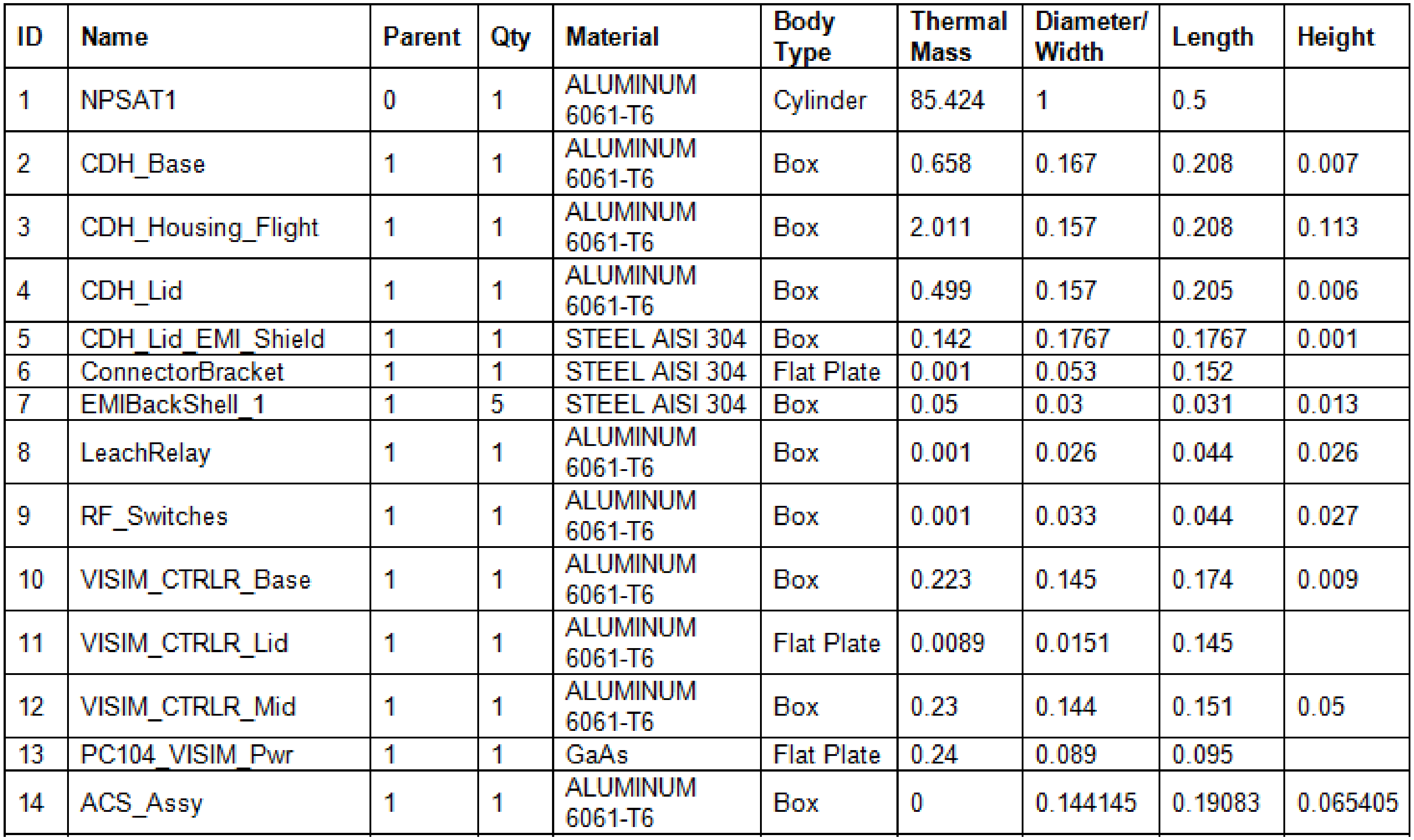
Table 4. DAS Input File for Reentry Analysis



ID	Name	Parent	Qty	Material	Body Type	Thermal Mass	Diameter/ Width	Length	Height
1	NPSAT1	0	1	ALUMINUM 6061-T6	Cylinder	85.424	1	0.5	
2	CDH_Base	1	1	ALUMINUM 6061-T6	Box	0.658	0.167	0.208	0.007
3	CDH_Housing_Flight	1	1	ALUMINUM 6061-T6	Box	2.011	0.157	0.208	0.113
4	CDH_Lid	1	1	ALUMINUM 6061-T6	Box	0.499	0.157	0.205	0.006
5	CDH_Lid_EMI_Shield	1	1	STEEL AISI 304	Box	0.142	0.1767	0.1767	0.001
6	ConnectorBracket	1	1	STEEL AISI 304	Flat Plate	0.001	0.053	0.152	
7	EMIBackShell_1	1	5	STEEL AISI 304	Box	0.05	0.03	0.031	0.013
8	LeachRelay	1	1	ALUMINUM 6061-T6	Box	0.001	0.026	0.044	0.026
9	RF_Switches	1	1	ALUMINUM 6061-T6	Box	0.001	0.033	0.044	0.027
10	VISIM_CTRLR_Base	1	1	ALUMINUM 6061-T6	Box	0.223	0.145	0.174	0.009
11	VISIM_CTRLR_Lid	1	1	ALUMINUM 6061-T6	Flat Plate	0.0089	0.0151	0.145	
12	VISIM_CTRLR_Mid	1	1	ALUMINUM 6061-T6	Box	0.23	0.144	0.151	0.05
13	PC104_VISIM_Pwr	1	1	GaAs	Flat Plate	0.24	0.089	0.095	
14	ACS_Assy	1	1	ALUMINUM 6061-T6	Box	0	0.144145	0.19083	0.065405

15	ACS_Base	1	1	ALUMINUM 6061-T6	Box	0.795	0.144145	0.19083	0.065405
16	ACS_Lid	1	1	ALUMINUM 6061-T6	Flat Plate	0.117	0.14351	0.19083	
17	ACS_PCB	1	2	GaAs	Box	0.16	0.1143	0.1651	0.0016
18	PCB_Standoff_cop	1	34	ALUMINUM 6061-T6	Flat Plate	1.3E-06	0.001	0.005	
19	CERTO Electronics	1	1	ALUMINUM 6061-T6	Box	1.066	0.076	0.133	0.051
20	EPS_Base	1	1	ALUMINUM 6061-T6	Box	0.802	0.149	0.19	0.065
21	EPS_Lid	1	1	ALUMINUM 6061-T6	Box	0.117	0.144	0.191	0.002
22	EPS_PCB_0	1	2	GaAs	Box	0.097	0.127	0.178	0.002
23	PCB_Standoff	1	34	ALUMINUM 6061-T6	Flat Plate	0.0001	0.005	0.015	
24	Langmuir Probe Box	1	1	ALUMINUM 6061-T6	Box	1.1	0.124	0.178	0.044
25	BattBox_Base	1	1	ALUMINUM 6061-T6	Box	0.495	0.171	0.215	0.005
26	BattBox_Cover	1	1	ALUMINUM 6061-T6	Box	1.351	0.171	0.244	0.078
27	SocketHeadCap_6-	1	36	STEEL AISI 304	Cylinder	0.002	0.006	0.016	
28	Li Ion Sony Cell	1	49	ALUMINUM 6061-T6	Cylinder	0.041	0.018	0.065	
29	Cell_Clamp_A	1	1	Polycarbonate (aka Lexan)	Box	0.105	0.137	0.178	0.006
30	Cell_Clamp_B	1	1	Polycarbonate (aka Lexan)	Box	0.102	0.137	0.178	0.006
31	ChoTherm	1	2	STEEL AISI 304	Flat Plate	0.001	0.137	0.171	

32	Gasket	1	1	STEEL AISI 304	Cylinder	0.001	0.002	0.568	
33	Hermetic Jam Nut	1	2	STEEL AISI 304	Cylinder	0.001	0.028	0.032	
34	Hex Socket Head	1	6	STEEL AISI 304	Cylinder	0.006	0.004	0.07	
35	Kapton Heater	1	1	ALUMINUM 6061-T6	Flat Plate	0.001	0.025	0.025	
36	Li Ion Ckt Board	1	1	ALUMINUM 6061-T6	Box	0.035	0.064	0.095	0.007
37	Li Ion PCB Bracket	1	2	ALUMINUM 6061-T6	Box	0.00013	0.005	0.01	0.001
38	Mini in-line Filte	1	1	ALUMINUM 6061-T6	Cylinder	0.0679	0.029	0.038	
39	Plug 1/4 in w/ O-r	1	2	STEEL AISI 304	Cylinder	0.0154	0.016	0.01	
40	PRV	1	1	ALUMINUM 6061-T6	Cylinder	0.017	0.018	0.025	
41	Solder Post	1	2	STEEL AISI 304	Cylinder	0.001	0.007	0.023	
42	ConnEnv_15pin	1	3	ALUMINUM 6061-T6	Box	0.001	0.013	0.039	0.012
43	ConnEnv_25pin	1	1	ALUMINUM 6061-T6	Box	0.001	0.013	0.053	0.012
44	JackScrewNut	1	8	STEEL AISI 304	Cylinder	0.001	0.006	0.013	
45	JunctionBoxBase	1	1	ALUMINUM 6061-T6	Box	0.37	0.074	0.159	0.043
46	JunctionBoxLid	1	1	ALUMINUM 6061-T6	Flat Plate	0.036	0.074	0.138	
47	JunctionPCB	1	1	GaAs	Box	0.001	0.056	0.122	0.002
48	JunctionPCB_Lower	1	1	Delrin	Box	0.0028	0.02	0.02	0.02
49	PCB Standoff	1	6	ALUMINUM 6061-T6	Flat Plate	0.0001	0.005	0.02	
50	Shunt_Resistor	1	2	STEEL AISI 304	Box	0.019	0.025	0.038	0.012

50	Shunt_Resistor	1	2	STEEL AISI 304	Box	0.019	0.025	0.038	0.012
51	EMI_BackshellA_1_4	1	5	STEEL AISI 304	Box	0.015	0.044	0.044	0.001
52	EMI_BackshellA_2_4	1	5	STEEL AISI 304	Box	0.015	0.044	0.044	0.001
53	SMS_Base	1	1	ALUMINUM 6061-T6	Box	1.164	0.149	0.191	0.075
54	SMS_Lid	1	1	ALUMINUM 6061-T6	Box	0.117	0.144	0.191	0.002
55	PCB_SMS_Standoff	1	68	ALUMINUM 6061-T6	Cylinder	0.00079	0.005	0.015	
56	SMS_PCB_0	1	4	GaAs	Box	0.156	0.127	0.178	0.002
57	AirCoil	1	2	ALUMINUM 6061-T6	Cylinder	0.235	0.027	0.152	
58	AirCoilWire	1	3	Copper Alloy	Box	1.395	0.1	0.16	0.1
59	AirCoil_Z	1	1	ALUMINUM 6061-T6	Cylinder	0.235	0.027	0.152	
60	CoilBracket_C	1	1	ALUMINUM 6061-T6	Box	0.143	0.076	0.076	0.048
61	Coil_Bracket	1	1	ALUMINUM 6061-T6	Box	0.213	0.077	0.102	0.047
62	Wheel Bracket A	1	1	ALUMINUM 6061-T6	Box	0.413	0.193	0.28	0.107
63	Wheel Bracket B	1	2	ALUMINUM 6061-T6	Flat Plate	0.488	0.248	0.251	
64	Magnetometer	1	1	ALUMINUM 6061-T6	Box	0.116	0.035	0.083	0.032
65	GPS_Antenna_ANTCOM	1	1	STEEL AISI 304	Box	0.001	0.053	0.053	0.015
66	MicroWheel 200	1	1	ALUMINUM 6061-T6	Cylinder	1	0.084	0.089	

66	MicroWheel 200	1	1	ALUMINUM 6061-T6	Cylinder	1	0.084	0.089	
67	Backshell_micro	1	1	ALUMINUM 6061-T6	Box	0.004	0.027	0.03	0.009
68	M83513_Conn_Face	1	1	ALUMINUM 6061-T6	Box	0.001	0.009	0.03	0.008
69	SMA_2Hole	1	1	ALUMINUM 6061-T6	Box	0.001	0.006	0.016	0.005
70	SQ-GPS-12-V1	1	1	ALUMINUM 6061-T6	Box	0.137	0.054	0.093	0.023
71	SP_Substr_Long_2A	1	12	ALUMINUM 6061-T6	Flat Plate	0.113	0.124	0.214	
72	SP_Substr_Short_2A	1	12	ALUMINUM 6061-T6	Box	0.191	0.124	0.19	0.003
73	SolarCells_4x9	1	12	GaAs	Flat Plate	0.015	0.111	0.183	
74	SolCells_4x10	1	24	GaAs	Flat Plate	0.015	0.111	0.203	
75	Baseplate Ground Pla	1	1	ALUMINUM 6061-T6	Flat Plate	1.541	0.28595	0.28595	
76	Quadrfillar_Ant_V0	1	2	Polycarbonate (aka Lexan)	Cylinder	0.7952	0.09	0.1	
77	NadirGP_Standoff	1	10	Copper Alloy	Cylinder	0.007	0.01	0.015	
78	SMA Flange Mount Jac	1	2	ALUMINUM 6061-T6	Cylinder	0.0102	0.013	0.029	
79	RFCoax_Bracket_A	1	2	ALUMINUM 6061-T6	Box	0.0088	0.01	0.041	0.008
80	RFCoax_Bracket_B	1	2	ALUMINUM 6061-T6	Box	0.0088	0.01	0.041	0.008

81	Diplexer	1	1	ALUMINUM 6061-T6	Box	0.822	0.44	0.76	0.182
82	CMOS_Housing_Cam1	1	1	ALUMINUM 6061-T6	Cylinder	0.254	0.133	0.051	
83	CMOS_Housing_Lid	1	1	ALUMINUM 6061-T6	Cylinder	0.116	0.095	0.038	
84	D-Sub EMIBackShell	1	1	STEEL AISI 304	Box	0.05	0.016	0.031	0.013
85	BraidedShieldInter	1	3	ALUMINUM 6061-T6	Cylinder	0.003	0.015	0.019	
86	Hex_Jam_Nut	1	2	STEEL AISI 304	Cylinder	0.003102	0.005	0.02	
87	Sun Sensor	1	6	ALUMINUM 6061-T6	Box	0.01	0.027	0.029	0.01
88	Sun Sensor Mount	1	3	ALUMINUM 6061-T6	Box	0.049	0.035	0.091	0.013
89	SunSensorCover	1	3	ALUMINUM 6061-T6	Box	0.043	0.03	0.076	0.019
90	SUNSENSOR_PCB	1	3	ALUMINUM 6061-T6	Box	0.001	0.031	0.076	0.001
91	EMI_Backshell_10	1	1	ALUMINUM 6061-T6	Cylinder	0.001	0.02	0.054	
92	Hermetic Jam Nut_1	1	1	STEEL AISI 304	Cylinder	0.001	0.032	0.028	
93	Hollow_Hex_Plug	1	2	ALUMINUM 6061-T6	Cylinder	0.000625	0.007	0.006	
94	MEMS Clamp	1	3	STEEL AISI 304	Flat Plate	0.009	0.048	0.048	
95	MEMS Gyro	1	3	ALUMINUM 6061-T6	Cylinder	0.04605	0.038	0.015	
96	MEMS Housing A	1	1	ALUMINUM 6061-T6	Cylinder	0.203	0.111	0.07	

97	MEMS Housing B	1	1	ALUMINUM 6061-T6	Box	0.299	0.1	0.111	0.01
98	MEMS O-RING	1	1	Viton	Cylinder	0.000376	0.001	0.256	
99	MEMS Tri-Axis Bracke	1	1	ALUMINUM 6061-T6	Box	0.102	0.052	0.054	0.046
100	bearing_sleeve	1	1	Rulon J	Cylinder	0.017	0.032	0.025	
101	bearing_thrust	1	2	Rulon J	Flat Plate	0.011	0.04731	0.04731	
102	compartment	1	1	ALUMINUM 6061-T6	Box	3.592	0.324	0.328	0.092
103	door	1	4	ALUMINUM 6061-T6	Box	0.085	0.045	0.304	0.008
104	gear_mate	1	1	ALUMINUM 6061-T6	Box	0.001	0.00761	0.00761	0.00761
105	holding_door	1	1	ALUMINUM 6061-T6	Box	0.203	0.06432	0.06432	0.06432
106	rod	1	4	STEEL AISI 304	Cylinder	0.01837	0.003	0.329	
107	spool_disc_top_gear	1	2	ALUMINUM 6061-T6	Box	0.012	0.03363	0.03363	0.03363
108	spool_without_clamps	1	1	ALUMINUM 6061-T6	Cylinder	0.058	0.048	0.026	
109	v_2_lid_1	1	1	ALUMINUM 6061-T6	Box	1.677	0.332	0.332	0.01
110	v_2_lid_2	1	1	ALUMINUM 6061-T6	Box	0.428	0.332	0.332	0.002
111	v_2_lid_3	1	1	ALUMINUM 6061-T6	Cylinder	0.287	0.07726	0.0996	
112	Space_no4	1	16	ALUMINUM 6061-T6	Cylinder	0.00069	0.005	0.013	

113	SP_JunctionPCB	1	4	GaAs	Flat Plate	0.012	0.045	0.063	
114	557-200M103C_Backshe	1	1	STEEL AISI 304	Box	0	0.02413	0.036855	0.012421
115	BaseSnake_01	1	1	Polycarbonate (aka Lexan)	Box	0.018	0.02	0.216	0.012
116	Base_Snake_01_Cover	1	1	Polycarbonate (aka Lexan)	Flat Plate	0	0.02	0.207	
117	Base_Snake_02	1	1	Polycarbonate (aka Lexan)	Box	0.018	0.02	0.216	0.012
118	Base_Snake_02_Cover	1	1	Polycarbonate (aka Lexan)	Flat Plate	0	0.02	0.207	
119	Deck3_Rev2	1	1	ALUMINUM 6061-T6	Box	7.345	0.4286	0.4286	0.01612
120	Flight_Baseplate	1	1	Aluminum 6061-T6	Box	6.6	0.4286	0.4286	0.01334
121	Flight_MidDeck	1	1	Aluminum 6061-T6	Flat Plate	5.589	0.274559	0.274559	
122	HarnessBulkhead_A	1	1	Aluminum 6061-T6	Box	0.059	0.049174	0.066396	0.016637
123	Lightband Base	1	1	ALUMINUM 6061-T6	Flat Plate	1.047	0.223798	0.223798	
124	Lightband Envelope	1	1	ALUMINUM 6061-T6	Flat Plate	1.151	0.249303	0.249303	
125	Longeron	1	3	ALUMINUM 6061-T6	Cylinder	0.53	0.03	0.277778	
126	Mid_Snake_01	1	1	Polycarbonate (aka Lexan)	Box	0.018	0.02	0.216	0.012
127	Mid_Snake_01_Cover	1	1	Polycarbonate (aka Lexan)	Flat Plate	0	0.02	0.207	
128	Mid_Snake_02	1	1	Polycarbonate (aka Lexan)	Box	0.018	0.02	0.216	0.012

129	Mid_Snake_02_Cover	1	1	Polycarbonate (aka Lexan)	Flat Plate	0	0.02	0.207	
130	ReleaseMech_NutPlate	1	2	STEEL AISI 304	Box	0.009	0.00762	0.03048	0.00635
131	Side Panel	1	3	ALUMINUM 6061-T6	Flat Plate	2.957	0.442	0.504	
132	16_694	1	4	STEEL AISI 304	Cylinder	0	0.003	0.007	
133	4 Duplicate3_596	1	6	STEEL AISI 304	Cylinder	0	0.003505	0.00856	
134	4 Duplicate4_640	1	1	STEEL AISI 304	Cylinder	0	0.006	0.008	
135	4_634	1	4	STEEL AISI 304	Cylinder	0.001	0.005	0.022	
136	8 Duplicate1_623	1	8	STEEL AISI 304	Cylinder	0.0006	0.004642	0.004642	
137	8 Duplicate2_603	1	3	STEEL AISI 304	Cylinder	0.001	0.006198	0.009728	
138	8_627	1	2	STEEL AISI 304	Cylinder	0	0.004	0.011	
139	CERTO_SMA_702	1	1	STEEL AISI 304	Cylinder	0.004	0.013	0.007	
140	CONE PIN_645	1	2	STEEL AISI 304	Cylinder	0	0.002	0.013	
141	CTI_Antenna_Shiel_16	1	2	ALUMINUM 6061-T6	Cylinder	0.031	0.013	0.137	
142	DELRIN COVER_642	1	2	DELRIN	Cylinder	0.0002	0.004572	0.012065	
143	DELRIN_643	1	4	DELRIN	Box	0.003	0.013	0.025	0.012
144	Hex Machine Scre_593	1	6	STEEL AISI 304	Box	0	0.002792	0.002792	0.002792
145	hinge pin_617	1	4	STEEL AISI 304	Cylinder	0.002	0.003175	0.032385	
146	LANGMUIR PROBE B_641	1	2	Steel AISI 304	Cylinder	0	0.016002	0.0127	
147	left hinge latch_619	1	2	ALUMINUM 6061-T6	Box	0.003313	0.017	0.024	0.003
148	left hinge_621	1	2	ALUMINUM 6061-T6	Box	0.005	0.017	0.032	0.006
149	Part1_639	1	2	ALUMINUM 6061-T6	Cylinder	0.002602	0.006	0.034	

150	Part2_638	1	2	ALUMINUM 6061-T6	Cylinder	0.008	0.012	0.045	
151	Part3_707	1	1	Aluminum 6061-T6	Cylinder	0	0.006	0.03	
152	Part4_646	1	1	Aluminum 6061-T6	Cylinder	0	0.01	0.029	
153	PINPULLER _P5_599	1	2	Aluminum 6061-T6	Cylinder	0	0.02761	0.041808	
154	pinpuller brkt2_606	1	2	ALUMINUM 6061-T6	Box	0.013	0.030226	0.035839	0.027686
155	Regular Helical _698	1	2	STEEL AISI 304	Box	0	0.002132	0.002132	0.002132
156	RELEASE BRKT SHI_591	1	4	ALUMINUM 6061-T6	Flat Plate	0.001	0.015874	0.015874	
157	release mech mtg_622	1	2	ALUMINUM 6061-T6	Flat Plate	0.019761	0.041793	0.041793	
158	release mech-HIN_600	1	4	STEEL AISI 304	Flat Plate	0	0.007937	0.007937	
159	release mech-PUS_601	1	2	STEEL AISI 304	Flat Plate	0.00079	0.01	0.01	
160	release mech-ves_607	1	16	Steel AISI 304	Box	0	0.00329	0.00329	0.00329
161	right hinge latc_615	1	2	ALUMINUM 6061-T6	Box	0.003313	0.017	0.024	0.003
162	right hinge_620	1	2	ALUMINUM 6061-T6	Box	0.005	0.017	0.032	0.006
163	SMA COPPER TUBE_682	1	1	Copper Alloy	Cylinder	0	0.004572	0.012065	
164	spring blk_616	1	2	STEEL AISI 304	Box	0.009	0.013	0.013	0.013
165	tube 1_683	1	1	ALUMINUM 6061-T6	Cylinder	0.000536	0.004572	0.012065	
166	tube 2_637	1	1	Aluminum 6061-T6	Cylinder	0.000536	0.004572	0.012065	
167	Type B - Plain W_628	1	10	STEEL AISI 304	Box	0	0.002683	0.002683	0.002683

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APPENDIX B. COMBINED SDAR/EOLP FORMAT DESCRIPTION

The following table summarized the individual sections specified by Requirement 5.4.4.1 of AFI 91–217. The intent of this information is to provide a general understanding of the document, the information it contains, and its context within the mission. Draft documents are typically submitted 30 to 45 days in advance of key mission milestones (such as the Preliminary Design Review and the Critical Design Review) but the final revision of the SDAR/EOLP must be submitted 30 days prior to beginning the launch approval process.

Table 5. Combined SDAR/EOLP Format Description

Summary of the Combined Spacecraft Debris Assessment Report / End-of-Life Plan	
Section	Summarized Content
Cover and Front Matter	The cover and opening pages of the document contain information regarding the document's version, who the signature authorities are, and the level of sensitivity required for handling the data contained within the document (e.g., security classifications, ITAR restrictions, release information).
Section 1: Program Management and Mission	This section identifies the program sponsoring the mission, who the program manager is, and lists all of the mission partners. Both design and program schedules are included along with milestones identified throughout the projected launch date. A separate schedule for operational milestones from launch to the spacecraft's end-of-life is also included. An overview of the spacecraft's mission, design, and launch parameters are included along with orbital parameters. These details include data such as the program's anticipated launch date, vehicle, launch site, and target orbital trajectory.

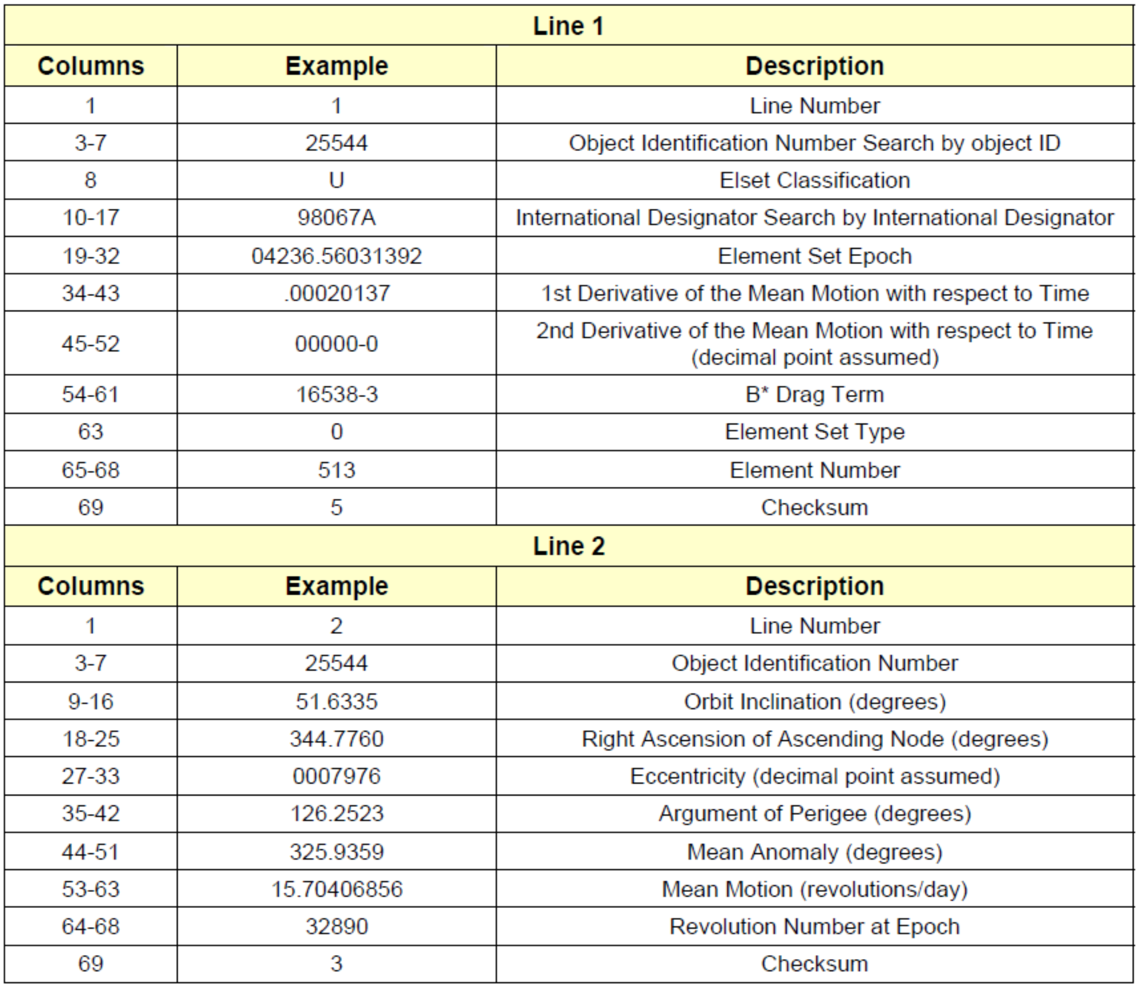
	A topical summary of the spacecraft's overall compliance with the debris mitigation requirements specified by DODI 3100.12 and AFI 91–217. Any object expected to be released throughout the spacecraft's lifetime is also listed in this section so long as the object has a diameter greater than 5 millimeters (mm).
Section 2: Spacecraft Description	Section 2 is the primary chapter within the combined SDAR/EOLP that provides the reader with a detailed description of the spacecraft. With discrete topics ranging from the spacecraft's dry (empty) and wet (fully fueled) masses to attitude control mechanisms. Not every program will have the systems or components that are required to be identified by AFI 91–217. For example, most spacecraft will not have radioactive materials on-board and smaller spacecraft (namely micro-satellites) will not have propulsion systems to save space. The spacecraft description is always accompanied by a detailed illustration of the satellite in its operational, or on-orbit, configuration.
Section 3: Assessment of Spacecraft Debris Released on Orbit	Much like Section 2, there will be several satellites that do not expect to release a single item of debris during operation or at the spacecraft's end-of-life. If a program does expect to release components into space during the mission, those objects with a diameter greater than 5 mm are expected to be identified. This list should also include the object's dimensions, mass, and material composition. For each identified object, the rationale behind the object's release is required; adding with it the velocity by which the object will be released, it's projected orbital trajectory, and estimated time of release. A detailed summary of the spacecraft's compliance with the relevant portions of DODI 3100.12 and AFI 91–217 is also required.

Section 4: Assessment of Spacecraft Potential for Explosions and Intentional Breakups	This section aims to provide the reader with a detailed summary of planned breakups (such as atmospheric reentry) and every realistic failure mode that could result in the spacecraft exploding. Passivation measures, or the act of depleting the spacecraft of all stored energy, and the components identified for passivation are also described in this section. If a component on the spacecraft requires passivation but there isn't a designed method to achieve it, those components need to be identified. Similar to the Section 3, the reason why these components are unable to be passivated along with the design rationale behind the reason need to be addressed. A detailed summary of the spacecraft's compliance with the relevant portions of DODI 3100.12 and AFI 91–217 is also required.
Section 5: Assessment of Potential for On-Orbit Collisions	Section 5, aims to identify the probability of a collisions on orbit. Aside from listing all of the components required to perform mission disposal this section mostly requires the use of the *Debris Assessment Software (DAS)*. Though the software was designed for use in NASA missions, AFI-217 references it directly for these calculations. The probabilities that the spacecraft will either collide with a known object larger than 10 cm in diameter or an object large enough to end the mission are both required. The results of these calculations are required along with an assessment of spacecraft's compliance with relevant paragraphs of DODI 3100.12.
Section 6: Assessment of Spacecraft Post-mission Disposal Plans and Procedures	In this section, the reliability of any post-mission disposal operation is considered along with detailed plans for passivation and an overview of the disposal method chosen. If atmospheric reentry is not the chosen disposal method for the spacecraft, the expected area-to-mass ratio of the spacecraft after disposal needs to be clarified.

	A detailed summary of the spacecraft's compliance with the relevant portions of DODI 3100.12 and AFI 91–217 is also required.
Section 7: Assessment of Spacecraft Reentry Hazards	This section requires each component within the spacecraft to be described though their individual dimensions, thermal mass, and material composition. The general shapes of these components are also required if the spacecraft will undergo atmospheric reentry. Similar to Section 5, the data specifically required by this section can be imported into either the *Debris Assessment Software* or another tool, *Object Reentry Survival Analysis Tool (ORSAT)*; both designed by NASA. Through either modeling program, the probability of human casualty resulting from a component reentering the atmosphere can be calculated. The results of these calculations are required along with an assessment of spacecraft's compliance with the relevant portions of DODI 3100.12 and AFI 91–217 is also required.
Section 8: Assessment for Tether Missions	Spacecraft that employ a tether must describe the type and design of the system. Information regarding the size of an object required to sever the tether, the lifetime on-orbit that a severed tether could survive, and the overall mission plan for the tether are all required. A detailed summary of the spacecraft's compliance with the relevant portions of DODI 3100.12 is also required; highlighting non-compliance.
Section 9: Reference List	The last section of the combined SDAR/EOLP gives the reader access to the technical data and resources used to author the document or perform the necessary calculations.

APPENDIX C. TWO LINE ELEMENT (TLE) DESCRIPTION

The Two-Line-Element (TLE) format is the main entry format used by the United States for cataloging spacecraft and man-made objects in space. Figure 10 details the meaning behind each of the values contained within a TLE entry. This reference can be used to understand the data present in the TLE entry for NOAA 14 (Table 1).



Line 1		
Columns	**Example**	**Description**
1	1	Line Number
3-7	25544	Object Identification Number Search by object ID
8	U	Elset Classification
10-17	98067A	International Designator Search by International Designator
19-32	04236.56031392	Element Set Epoch
34-43	.00020137	1st Derivative of the Mean Motion with respect to Time
45-52	00000-0	2nd Derivative of the Mean Motion with respect to Time (decimal point assumed)
54-61	16538-3	B* Drag Term
63	0	Element Set Type
65-68	513	Element Number
69	5	Checksum
Line 2		
Columns	**Example**	**Description**
1	2	Line Number
3-7	25544	Object Identification Number
9-16	51.6335	Orbit Inclination (degrees)
18-25	344.7760	Right Ascension of Ascending Node (degrees)
27-33	0007976	Eccentricity (decimal point assumed)
35-42	126.2523	Argument of Perigee (degrees)
44-51	325.9359	Mean Anomaly (degrees)
53-63	15.70406856	Mean Motion (revolutions/day)
64-68	32890	Revolution Number at Epoch
69	3	Checksum

Figure 9. Two Line Element (TLE) Format Description

Source [5]: *Handbook for Limiting Orbital Debris*, NASA-HDBK-8719.14, NASA, Washington, DC, 2008, pp. 42–59.

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APPENDIX D. COMPARISON BETWEEN U.S. AIR FORCE AND NASA REQUIREMENTS WITH RESPECT TO DAS

The Debris Assessment Software (DAS) was designed for NASA mission planners to quickly determine whether their spacecraft was fully compliant. The metric of being compliant is determined through ten different tool sets, or models, within DAS. Each model computes spacecraft specific data, entered into by the operator, against one of the requirements levied by NASA-STD-8719.14A. Given the utility of this tool, the following comparison aims to help military spacecraft programs quickly reference their compliance with AFI 91–217 through the use of DAS. The following table compares the compliance requirements by both agencies side by side as they relate to the ten different computational tools in DAS.

Table 6. DAS Compliance Analysis

<table>
<tr><th colspan="2">DAS Compliance Analysis by Requirement</th></tr>
<tr><th>Relevant NASA-STD-8719.14A Requirement [32]</th><th>Equivalent AFI 91–217 Requirement [24]</th></tr>
<tr><td colspan="2">Mission-Related Debris Passing Through LEO</td></tr>
<tr><td>Requirement 4.3–1: Debris passing through LEO - released debris with diameters of 1mm or larger:

Requirement 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 (Requirement 56398).

Requirement 4.3–1b: The total object-time product shall be no larger than 100 object-years per mission (Requirement 56399). The object-time product is the sum of all debris of the total time spent below 2,000 km altitude during the orbital lifetime of</td><td>5.4.5.1. Debris passing through Low-Earth Orbit (LEO). For missions leaving debris in orbits passing through LEO, released debris with diameters of 5 mm or larger shall have maximum orbital lifetimes of 25 years from date of release. The total object-time product shall not exceed 100 object-years per mission. The object-time product is the sum over all debris of the total time spent below 2000 km altitude during the orbital lifetime of each object. Reference NASA-STD-8719.14A.</td></tr>
</table>

each object.	
Mission-Related Debris Passing Near GEO	
Requirement 4.3–2: Debris passing near GEO: For missions leaving debris in orbits with the potential of traversing GEO (GEO altitude +/- 200 km and +/- 15 degrees latitude), released debris with diameters of 5 cm or greater shall be left in orbits which will ensure that within 25 years after release the apogee will no longer exceed GEO - 200 km (Requirement 56400).	5.4.5.2. Debris passing near Geosynchronous Orbit (GEO). For missions leaving debris in orbits with the potential of traversing GEO (GEO altitude +/- 200 km and +/- 15 degrees latitude), released debris with diameters of 5 cm or greater shall be left in orbits which will ensure that within 25 years after release the apogee will no longer exceed GEO - 200 km. Reference NASA-STD-8719.14.
Long-Term Risk from Planned Breakups	
Requirement 4.4–3. Limiting the long-term risk to other space systems from planned breakups: Planned explosions or intentional collisions shall: a. Be conducted at an altitude such that for orbital debris fragments larger than 10 cm the object-time product does not exceed 100 object-years (Requirement 56453). For example, if the debris fragments greater than 10cm decay in the maximum allowed 1 year, a maximum of 100 such fragments can be generated by the breakup. b. Not generate debris larger than 1 mm that remains in Earth orbit longer than one year (Requirement 56454).	5.4.7.1. Planned explosions or intentional collisions shall occur at altitudes such that, for orbital debris fragments larger than 10 cm, the object-time product does not exceed 100 object-years. No debris larger than 1 mm shall remain in Earth orbit longer than 1 year. Reference NASA-STD-8719.14A. 5.4.7.2. Immediately before a planned explosion or intentional collision, the probability of related debris larger than 1 mm colliding with any active spacecraft within 24 hours of the breakup shall not exceed 1 10–6 (one in one million). Reference NASA-STD 8719.14A.
Probability of Collision with Large Objects	
Requirement 4.5–1. Limiting debris generated by collisions with large objects when operating in Earth orbit: For each	5.4.8.1. Collisions with Large Objects. Programs shall demonstrate that, during the

spacecraft and launch vehicle orbital stage in or passing through LEO, the program or project shall demonstrate that, 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 (Requirement 56506).	orbital lifetime of each spacecraft or launch vehicle component in or passing through LEO, the probability of accidental collision with space objects larger than 10 cm in diameter is less than 1 10–3 (one in one thousand). Reference NASA-STD 8719.14.
Probability of Damage from Small Objects	
Requirement 4.5–2. Limiting debris generated by collisions with small objects when operating in Earth or lunar orbit: For each spacecraft, the program or project shall demonstrate that, 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 requirements is less than 0.01 (Requirement 56507).	5.4.8.2. Collisions with Small Objects. Programs shall demonstrate that, during the mission of the space system, the probability of accidental collision with objects (including space debris and meteoroids) sufficient to prevent post-mission disposal is less than 1 10–2 (one in one hundred). Reference NASA-STD-8719.14.
Postmission Disposal	
Requirement 4.6–1. Disposal for space structures in or passing through LEO: A spacecraft or orbital stage with a perigee altitude below 2,000 km shall be disposed of by one of the following three methods: (Requirement 56557) a. Atmospheric reentry option: • Leave the space structure in an orbit in which natural forces will lead to atmospheric reentry within 25 years after the completion of mission but no more than 30 years after launch; or • Maneuver the space structure into a controlled de-orbit trajectory as soon as practical after completion of mission.	5.7.3.1.1. Uncontrolled Atmospheric Reentry. Leave the spacecraft or launch vehicle component in an orbit in which natural forces will lead to atmospheric reentry within 25 years after the end of mission. 5.7.3.2.1. When selecting disposal orbits, operators shall account for spacecraft area/mass ratio and the effect of future orbital drift due to gravitational perturbations and other space environmental effects. Due to fuel gauging uncertainties near the end of mission, use a maneuver strategy that has the least risk of

b. Storage orbit option: Maneuver the space structure into an orbit with perigee altitude greater than 2000 km and apogee less than GEO - 500 km. c. Direct retrieval: Retrieve the space structure and remove it from orbit within 10 years after completion of mission. Requirement 4.6–2. Disposal for space structures near GEO: A spacecraft or orbital stage in an orbit near GEO shall be maneuvered at EOM to a disposal orbit above GEO with a predicted minimum perigee of GEO +200 km (35,986 km) or below GEO with an apogee of GEO—200 km (35,586 km) for a period of at least 100 years after disposal (Requirement 56563). Requirement 4.6–3. Disposal for space structures between LEO and GEO: a. A spacecraft or orbital stage shall be left in an orbit with a perigee greater than 2000 km above the Earth's surface and apogee less than 500 km below GEO (Requirement 56565). b. A spacecraft or orbital stage shall not use nearly circular disposal orbits near regions of high value operational space structures, such as between 19,200 km and 20,700 km (Requirement 56566).	leaving the structure near an operational orbit regime. 5.7.3.3. Direct retrieval. Direct retrieval strategies shall comply with all disposal requirements in this AFI and in the ODMSP.
Casualty Risk from Reentry Debris	
Requirement 4.7–1. Limit the risk of human casualty: The potential for human casualty is assumed for any object with an impacting kinetic energy in excess of 15 joules: a. For uncontrolled reentry, the risk of	5.7.3.1.1.1. The collective risk to the general public due to uncontrolled atmospheric reentry shall not exceed a casualty expectation (Ec) of 100 x 10–6 (one hundred in one million). 5.7.3.1.2. Controlled Atmospheric

human casualty from surviving debris shall not exceed 0.0001 (1:10,000) (Requirement 56626). b. For controlled reentry, the selected trajectory shall ensure that no surviving debris impact with a kinetic energy greater than 15 joules is closer than 370 km from foreign landmasses, or is within 50 km from the continental U.S., territories of the U.S., and the permanent ice pack of Antarctica (Requirement 56627). c. For controlled reentries, the product of the probability of failure of the reentry burn (from Requirement 4.6–4.b) and the risk of human casualty assuming uncontrolled reentry shall not exceed 0.0001 (1:10,000) (Requirement 56628).	Reentry. For controlled reentry of any orbiting object, the selected trajectory shall comply with the requirements in Section 4.6. *4.6.3.1. Public. The risk to the general public shall not exceed an individual Probability of Casualty (Pc) of 1 x 10–6 (one in one million), and the collective risk to the general public shall not exceed a casualty expectation (Ec) of 100 x 10–6 (one hundred in one million). Each major component of a mission shall have a separate risk budget (e.g., upper stage allocated 100 10–6 and the spacecraft allocated 100 10–6). Reference RCC 321.*
Collision Hazards of Space Tethers	
Requirement 4.8–1. Mitigate the collision hazards of space tethers in Earth or Lunar orbits: Intact and remnants of severed tether systems in Earth and lunar orbit shall meet the requirements limiting the generation of orbital debris from on-orbit collisions (Requirements 4.5–1 and 4.5–2) and the requirements governing postmission disposal (Requirements 4.6–1 through 4.6–4) to the limits specified in those paragraphs (Requirement 56652).	(Not Available)

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