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Project Scrappie (Clear Constellation)

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Executive Summary

Clear Constellation™ is a nationwide competition hosted by Rubicon® to combat the growing problem of space debris in Low Earth Orbit. The competition is to design a process or apparatus that can help to eliminate this issue and will be judged by six reputable individuals.

Project Scrappie is an autonomous, space debris collecting apparatus that will effectively clear orbital paths for satellites or other spacecrafts in Low Earth Orbit. Scrappie will be transported to the International Space Station via leased rocket space on SpaceX's Falcon Heavy. Upon arriving at the International Space Station, Scrappie will dock and be prepared for upcoming missions. For missions, Scrappie will be deployed into the desired orbital paths ahead of the satellite or spacecraft that needs the path cleared. While in the orbital path, Scrappie will autonomously collect any debris that is 10 cm in diameter or less. Any debris that is larger than 10 cm in diameter will be avoided as this debris is actively tracked and already avoided by space apparatuses. Upon completion of clearing the orbital path to the best of Scrappie's ability, Scrappie will return to the International Space Station to redock and receive any maintenance it may need.

The main feature of Scrappie is the debris collection method. Scrappie will make use of Whipple Shield technology to collide with debris at high velocities and effectively destroy the debris. Scrappie's propulsion system will be composed of gridded-electrostatic ion thrusters that allow for efficient and steady propulsion. The power supply will be provided by two solar panels that can rotate around Scrappie and reconfigure to acquire the maximum amount of power. The infrastructure will be entirely fabricated of aluminum alloy to ensure a structurally sound apparatus that can withstand multiple high velocity collisions.

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1.0 Project Overview

1.1 System Overview and Objective

The Scrappie spacecraft will be an autonomous system used for cleaning up and clearing out space debris in the Low Earth Orbit (LEO). The apparatus will be transported to the International Space Station (ISS) and deployed into low orbit. Once in orbit, Scrappie will be able to maneuver using gridded electrostatic ion (GEI) thrusters. This type of mechanism will use a Whipple shielding approach in attempt to 'idle’ the clearing of debris. Whipple shielding is a hypervelocity impact shield designed to protect crewed and uncrewed spacecraft against micrometeoroids and orbital debris with velocities ranging from 3 to 18 kilometers per second. The debris will be destroyed and taken to the ISS to be unloaded and sent back down to Earth for researching or logging purposes. The major components involved in the creation of Scrappie will be made up of two solar panels, GEI thrusters, thruster system, and guidance sensors. The solar panels will be used to harness solar power to charge the spacecraft when in space to avoid the situation of losing energy for the electrical instruments while carrying out a mission. The sensors will allow Scrappie to have the ability to move around in space autonomously and position itself correctly to allow for the maximum amount of energy to be harnessed by the solar panels. They will also allow Scrappie to determine where and when to collect or dodge oncoming debris. Thrusters will be used to guide the spacecraft in low orbit as well as increase velocity to ensure debris being collected is contacting the Whipple shield with an adequate amount of force.

Scrappie will be the initial design concept for this process, however, the end objective for this project is to develop a Scrappie that can be used in unison with multiple, identical Scrappies in tandem. The idea will be that one Scrappie can connect to multiple other Scrappies and be set on an orbital path that a satellite, or another object is set to use. From here, the connected Scrappies will clear this orbital path and effectively remove all debris that would potentially collide with the satellite/object set to this orbital path.

1.2 Project Background and Problem Statement

In Low Earth Orbit there is a known problem of free drifting debris varying in size that could be detrimental if it encounters a shuttle or satellite. It is known that there are approximately 36,500 pieces of debris that are greater than or equal to 10 cm in size (approximately the size of a softball or larger) and approximately 331,000,000 pieces of debris that are smaller than that throughout LEO [1]. The objects that are greater than 10 cm are tracked by various satellites and are considered dangerous for most missions. However, objects that are smaller than 10 cm are not tracked and present an equally large problem. This problem, if it continues to persist, could effectively prevent future space missions from occurring. To combat this growing issue, our team has designed an apparatus aimed at collecting debris of size 10 cm or less and have it properly disposed of.

2.0 Literature Review

2.1 Removal and Propulsion Methods

The cleanup of orbital debris has become a crucial aspect of commercial and scientific space management. It's an accumulating issue that needs to be handled right away to avoid spacecraft loss due to junk collisions. Collective, laser-based, ion-beam shepherd-based, tether-based, sail-based, satellite-based, unconventional, and dynamical systems-based approaches are all classed [1]. An ADR mission scenario can be thought of as consisting of different phases in which a deorbiting platform is in charge of approaching a target debris, bringing it to a lower altitude orbit, and, in the case of a multiple-target mission, releasing it and chasing a second one, regardless of the method identified as the most suitable. Given the high total impulse typical of these missions, electric propulsion (EP) is critical for lowering the propellant mass consumption necessary for each maneuver and therefore increasing the mass available to deorbit a significant amount of debris per mission [2].

2.2 Large Cargo Transportation Methods

Scrappie will be a large apparatus that will be able to maneuver by itself once in orbit. However, it will not be able to independently get into orbit, it will need the assistance of an actual rocket ship to get there [3]. Due to this, the launching of the James Webb Space Telescope has been of interest since a major difficulty is getting a large apparatus into space. The Webb Telescope will be riding within the Ariane 5's cargo space at the front/top of the rocket. The Ariane 5 has a useable cargo space of 4.57 meters in diameter and 16.19 meters in length which the telescope can fit into once it is in a folded configuration. This rocket can also carry up to 20 metric tons of cargo into LEO which makes it an ideal candidate for getting Scrappie to its destination [4].

Similar to the Ariane 5, SpaceX's Falcon Heavy is another rocket ship that is capable of getting Scrappie out to our desired orbit path in LEO. This rocket has a payload size of 5.2 meters in diameter and 13.1 meters in length and an impressive ability to get 63.8 metric tons of cargo into LEO [5] [6]. The thrust needed to get that large of a payload is equal to 18 747 aircrafts at full throttle [6]. Though Scrappie's weight is not even close to that magnitude, at its weight of 8.5 metric tons, it would be an estimated price of $42.5 million to get the apparatus into LEO. The ability to get an estimate to get Scrappie into LEO makes Falcon Heavy the most plausible choice of rocket ship.

2.3 Spacecraft Materials

The material used for the design of Scrappie is a critical problem area of its design. We want to choose a material that is strong in order to survive the harsh conditions of LEO, while also being lightweight as to not inflate the cost to put it into orbit. There are a few main candidates for materials, all of which are aluminum alloys [7]. AA 2024 is the most commonly used alloy in aerospace due to its high strength-to-weight ratio. This alloy should be considered as the main material Scrappie will be composed of. AA 2014 is another popular alloy. It is mainly used on the interior sections of aircraft due to its low resistance to corrosion. However, because of the nature of Scrappie's mission purpose, AA 2014 will not be considered for the design. Other alloys up for consideration are AA 7075, AA 7050, and AA 7068.

2.4 Energy Methods

Solar arrays are a very large part of a space craft's ability to maintain consistent electrical power. Scrappie is going to be working constantly and with all the different components that it'll be using, lots of electrical power is going to be required. Solar arrays started out, 60 years ago, with only 6 % efficiency, today they have over 50% efficiency [8]. Having much better efficiency allows for more electrical power to be produced, which will be important since Scrappie possible methods of collection and propulsion will each require a large amount of consentient electrical power. The amount of electrical power that the ISS uses is 215 kilowatts, and the life span of the arrays is 15 years [9], which is almost double the electrical power used and arrays life span of most other space crafts.

3.0 Project Details and Requirements

3.1 Design Requirements and Specifications

Scrappie will be transported to and from the ISS via leased payload space within an existing rocket. Allowing it to survive orbital exit and re-entering conditions. Based off the payload dimensions for multiple plausible rockets, it was determined that Scrappie should be 3 meters in diameter and 3 meters in length with a total weight of 8.5 metric tons to accommodate these requirements. Since Scrappie will be deployed into dangerous conditions, another requirement is that it is operated autonomously. Automation will be done via sensors located in multiple different locations along Scrappie that can determine desired flight path, any possible dangers, and the type of debris needing to be collected.

Scrappie’s propulsion system will be composed of gridded electrostatic ion (GEI) thrusters with xenon as propellant. These types of thrusters are a form of ion thrusters which rely on Coulomb force to accelerate ions in the direction of an electric field [10]. These electric fields are generated by electrodes called ion optics or grids and consist of thousands of coaxial apertures [10]. The GEI used for Scrappie will be a two-electrode system that relies on an upstream electrode (the screen grid) and a downstream electrode (the accelerator grid) to create highly positive and negative charges, respectively [10]. The highly charged ions from the screen grid are attracted to the negatively charged ions from the accelerator grid [10]. This attraction creates thousands of ion jets that are directed out of the discharge chamber forming the ion beam [10]. The top speed of these types of thrusters is limited by the amount of voltage being applied to the ion optics, which theoretically should be unlimited [10]. The power supplied to the thrusters will be from advanced power processing units (PPU) to supply the adequate amount of voltage needed.

To navigate Scrappie through the conditions of Earth's low orbital atmosphere, there will be an onboard operating computer using SMART Nav technology similar to the one included in the guidance, navigation, and control system (GNC) for NASA's DART spacecraft. This system makes use of sun sensors and star trackers to autonomously guide spacecrafts on their desired paths [11].

Scrappie will have its electrical components powered by solar energy that make use of Transformational Solar Array technology. This technology effectively triples the amount of energy harnessed when compared to normal solar arrays [11]. This solar array configuration will be similar to the ones currently used on the ISS and DART. Scrappie will abide by NASA's Technical Standards System and U.S. Department of Commerce's Space Standards.

Requirements:

- Scrappie shall be able to survive atmospheric exit and re-entering conditions
- Scrappie shall be able to collect/clear debris of various velocities without sustaining damage
- Scrappie shall be able to be controlled remotely at mission base and/or ISS
- Scrappie shall weigh no more than 10 metric tons
- Scrappie shall be able to last until system failures (Whipple Shield needing replacement, refueling, etc.)
- Scrappie shall be able to transport and collect 2 metric tons of weight
- Scrappie shall have a 3 m max diameter, with a 4 m max length
- Scrappie shall be able to avoid oncoming hazards
- Scrappie shall be able to fly/move/navigate through space conditions
- Scrappie shall be able to hold applicable amount of propellent for thrust/propulsion
- Scrappie shall be able to achieve and maintain speeds necessary for orbit

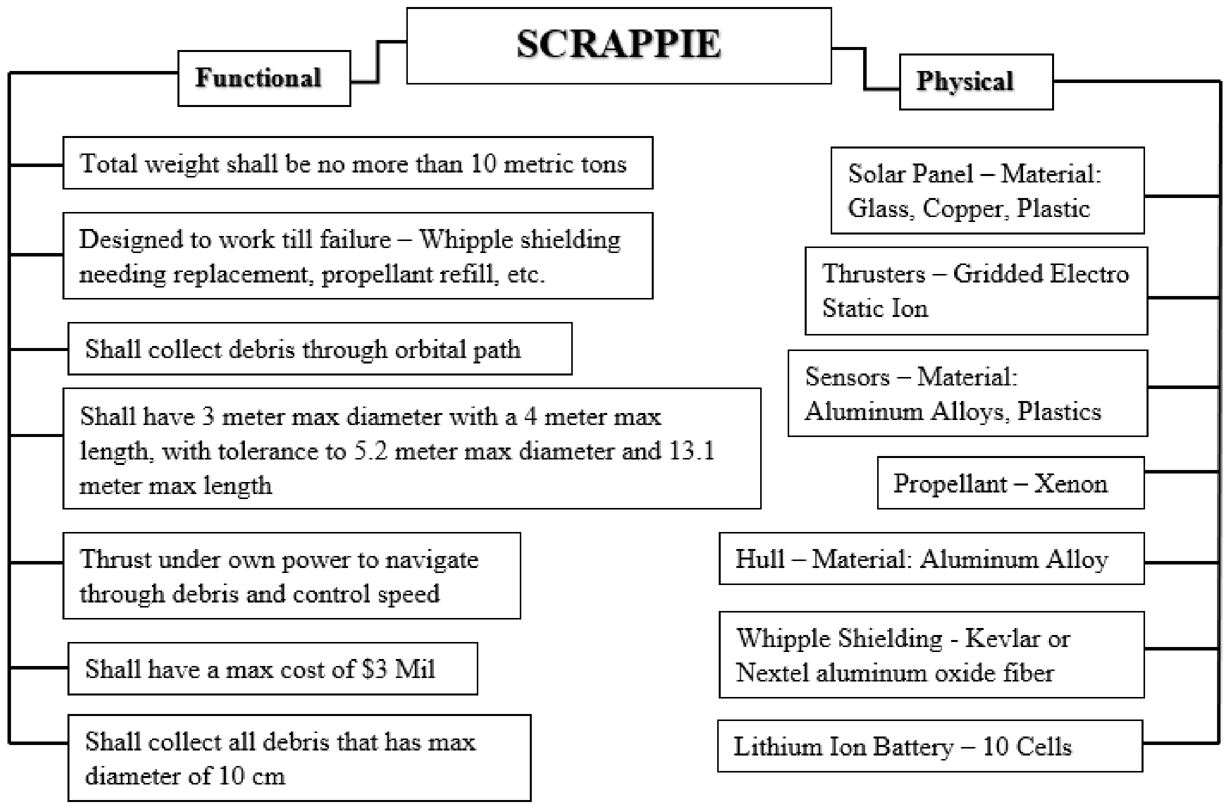
- Scrappie shall cost no more than $3.0 mil
- Scrappie shall be up to applicable codes and standards
- Scrappie shall have electronics maintained via solar energy

3.2 Major Developments

- Concept Brainstorming
- Concept Research
    - IDR – 8/23
- Design Selection
- Design Research
    - PDR – 9/27
    - IPR - 10/25
- Testing Design and Analysis
    - CDR – 11/15
- Reworking Design
- Final Product (Report/Presentation)
    - FDR – 12/6
- Competition Submission Deadline - 2/28
- Competition Winner Announcement – 5/1

3.3 System Block Diagrams

Table 1: Block Diagram



3.4 Minimum Success Criteria

Designing an applicable apparatus to collect, transport, and/or remove space debris from Low Earth Orbit (LEO).

3.5 Verification Approach: Calculations

3.5.1 Velocity Loss on Impact – Conservation of Momentum

To determine Scrappie's loss of velocity after each impact with debris, conservation of momentum will be used to calculate the final velocity of the craft.

$$m_1 v_1 + m_2 v_2 = m_1' v_1' + m_2' v_2'$$

Where m_1 and v_1 are the mass and velocity of the craft, respectively, and m_2 and v_2 are the mass and velocity of the debris, respectively. Terms on the left side of the equation denote values before impact, and terms on the right side of the equation denote after impact.

The velocity of the debris after impact will be zero ($v_2' = 0$), since it will be stopped by the craft. The mass of the craft after impact will be the sum of the mass of craft and debris before impact ($m_1' = m_1 + m_2$), since the debris will have been captured by the craft. Solving for velocity of the craft after impact yields:

$$v_1' = \frac{m_1 v_1 + m_2 v_2}{m_1 + m_2}$$

And velocity loss on impact can be shown by the difference velocity before and after impact:

$$\Delta v = v_1 - v_1'$$

The average mass of debris in LEO (calculated using mass density data) is found to be approximately 0.00003 kg, however, there is no significant difference between the change in velocity for debris with a mass of 0.001 kg and debris with a mass << 0.001 kg. Therefore, the range for debris mass (m_2) will be from 0.001 kg to 1.4 kg.

The average velocity of debris in LEO is found to range from 7.8 km/s to 10.0 km/s. So, we will calculate for debris velocities (v_2) of 7.8 km/s, 8.9 km/s, and 10.0 km/s.

The mass of the craft used will be 8,493.09 kg. Note that this value is inversely proportional to the final change in velocity, that is $m_1 \propto \frac{1}{\Delta v}$. So, as the mass of the craft increases the change in velocity will decrease. Therefore, it would be beneficial to increase the mass of the craft to minimize loss in velocity. However, an increase in mass will increase the force necessary to accelerate the craft. These are factors to keep in mind when optimizing the mass of the craft.

The velocity of the craft will be assumed to be 7.8 km/s. This value is based on the lower range of velocity of debris in LEO. Orbital velocity for LEO can range between 6.5 km/s to 8.2 km/s depending on altitude and shape of the orbit.

Solving for Δv yields the following plot:

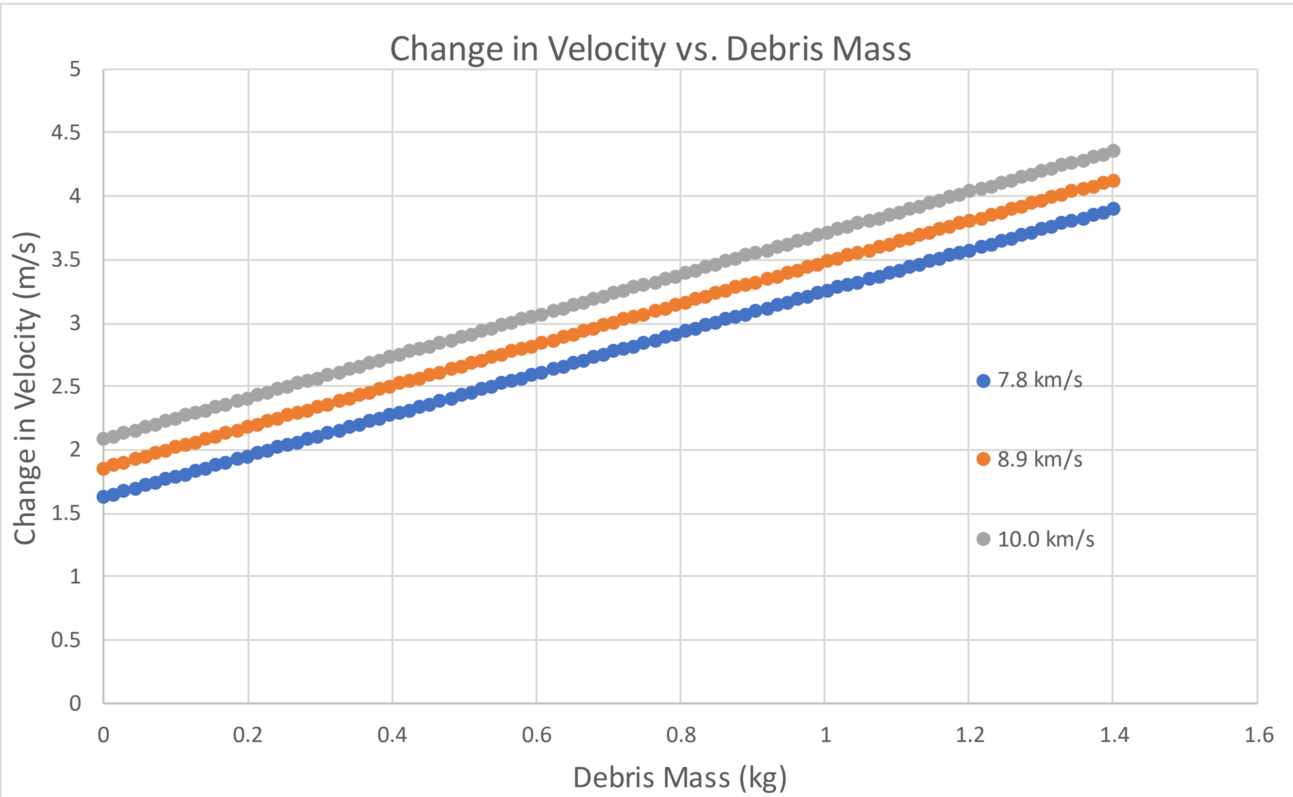


Figure 1: Change in Velocity vs. Debris Mass

Where the debris mass (m_2) in kg is shown on the x-axis, and the resultant change in velocity (Δv) in m/s is shown on the y-axis. From this plot, we can see that the minimum loss in velocity for any impact with debris with a minimum velocity of 7.8 km/s is 1.85 m/s. The max value occurs with debris with a mass of 1.4 kg with a velocity of 10.0 km/s, which results in a 4.35 m/s loss in velocity.

Because the average mass of debris is << 0.001 kg, instances where the craft collides with debris with a mass of 0.5 kg or greater will be viewed as an uncommon event. So, the average debris collision will be assumed to result in a max loss of velocity of 3.0 m/s.

3.5.2 Fuel Mass Flux – Specific Impulse

To determine the amount of fuel consumed per unit time by the thrusters used, the specific impulse equation will be used. The specific impulse equation is as follows:

$$F_t = g_0 I_{sp} \dot{m}$$

Where F_t is the thrust generated by the thruster in Newtons, g_0 is standard gravity, I_{sp} is the specific impulse of the thruster in seconds, and $\dot{m}$ is fuel mass flux in kg/s. Solving for fuel mass flux yields:

$$\dot{m} = \frac{F_t}{g_0 I_{sp}}$$

The thrusters to be used on this craft are the NEXT-C ion thrusters. These thrusters have a maximum specific impulse (I_{sp}) of 4220 seconds and produce a thrust (F_t) of 235 mN per thruster. Scrappie's design calls for three thrusters so the total thrust produced will be 705 mN.

Solving for mass flux ($\dot{m}$) yields 5.6823E-06 kg/s, or 0.00568 g/s. With a fuel tank with a capacity of 50 kg, this gives our craft 100 days of constant burn time. It should be noted that the thrusters will not be constantly engaged while in orbit. Fuel will only be burned to make up for loss velocity, to perform maneuvers to avoid large debris, or other emergency situations.

3.5.3 Whipple Shield Dimensioning

The Whipple shield will consist of two aluminum plates separated by a layer of Kevlar as shown in the figure below.

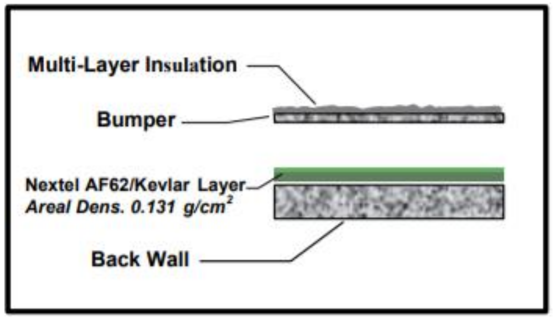


Figure 2: Whipple Shield Layout

The front face of the shielding, called the bumper, will be the face that debris strike on impact. The Kevlar layer, called stuffing, is meant to collect the debris after being vaporized by the bumper. The last layer, or back wall, is used as a safety measure in the even that debris is not completely vaporized by the bumper.

The critical diameter for penetration of the Whipple shield is dependent primarily on the material and dimensioning of the shield, as well as other factors. The equation for the critical diameter of debris for penetration of the shields is:

$$d_c = \frac{A \cdot t_w^{\frac{2}{3}} \cdot \left(\frac{\sigma}{70}\right)^{\frac{1}{3}}}{(cos\theta)^{\frac{4}{3}} \cdot \rho_P^{\frac{1}{3}} \cdot \rho_b^{\frac{1}{9}} \cdot V^{\frac{2}{3}} \cdot S^{-\frac{1}{3}}}$$

Where d_c is the critical diameter for penetration, t_w is the thickness of the back wall, V is the impact velocity normal to the bumper, S is the distance between the bumper and back wall, and θ is the impact angle. ρ_p and ρ_b are the material densities of debris and bumper, respectively. A is a constant that depends on the configuration of multi-layer insulation (MLI) and Kevlar stuffing. The values for A are as follows:

Table 2: Whipple Shield Equation Constants

Shield with MLI on Bumper	A = 2.9754
Shield without MLI	A = 3.918
Stuffed Shield with MLI on Bumper	A = 5.2002

Scrappie will feature a stuffed shield with MLI on the bumper, so a value of 5.2002 will be used for the constant A in the calculation of shield dimensions. The shield will use AA 2024-T4 which has a density (ρ_b) of 2.78 $\frac{g}{cm^3}$ and yield strength (σ) of 40 ksi. Because there is little information about the materials that space debris is primarily composed of, the same material density will be assumed for the debris (ρ_p), as this alloy is the most common alloy used in spacecraft. A maximum velocity of 10.0 km/s will be used, and the impact angle will be assumed to be normal to the bumper plate.

The design requirements for Scrappie require that it be capable of collecting debris of size 10 cm or less, so this will be the critical diameter (d_c). The thickness of the back wall (t_w) and distance between the bumper and back wall (S) are variables that can be iterated depending on design needs.

The design will use a bumper plate and back wall with a thickness of 2.4 cm and 12 cm, respectively. The space between the bumper plate and back wall will be 47 cm, and this space will be stuffed with Kevlar.

3.6 Budget

Table 3: Cost of Materials and Components

Item	Cost	Quantity	Subtotal
Craft*			
Various Plating	$1,400	1	$1,400
Main Shell	$16,500	1	$16,500
Whipple Shield	$16,400	1	$16,400
Thrusters			
NEXT-C Ion Thruster	$500,000	3	$1,500,000
Xenon – Propellant	$2,000 per kg	50 kg	$100,000
Power			
Solar Array	$7,000 per kW	50 kW	$350,000
30Ah Lithium-Ion Cell	$700 per cell	10	$7,000
Power Processing Unit (PPU) (Price included in Thrusters)	$364,000	2	$728,000
Optics			
Sun Sensor	$12,000	4	$48,000
Star Tracker	$52,000	2	$104,000
		Total	~$2,144,000

*Pricing of Craft components are an estimation based on current design and is subject to change.

3.6.1 Launch

Table 4: Cost per Kilogram to Send Payload into Low-Earth Orbit (LEO):*

Rocket	Cost per kg
Falcon Heavy (SpaceX)	$5,000
Falcon 9 v1.1 (SpaceX)	$4,109
DNEPR (Yuzhnoye)	$3,784
Delta IV (ULA)	$13,072
Atlas V (ULA)	$13,182

*LEO is defined as an orbit with an altitude of less than 2000 km (1200 mi)

3.6.2 Materials

Table 5: Materials List

Item	Cost per kg*
Aluminum	$2.30
Kevlar	$15.00
Titanium	$30.00

*Displayed cost is for material only and does not consider manufacturing cost.

- Aluminum – Current satellites and other man-made objects in orbit are mainly composed of aluminum alloys due to its high strength to weight ratio
- Kevlar – This material is used to reinforce the outer surfaces of satellites to withstand heat, pressure, etc. during launch. However, Kevlar will be used as a lining for the Whipple shielding for this craft.
- Titanium – Although a strong material, titanium is too dense of a metal to be used on a craft designed to be sent into orbit, as the cost would increase considerably.

3.7 Team Assignment and Overall Schedule

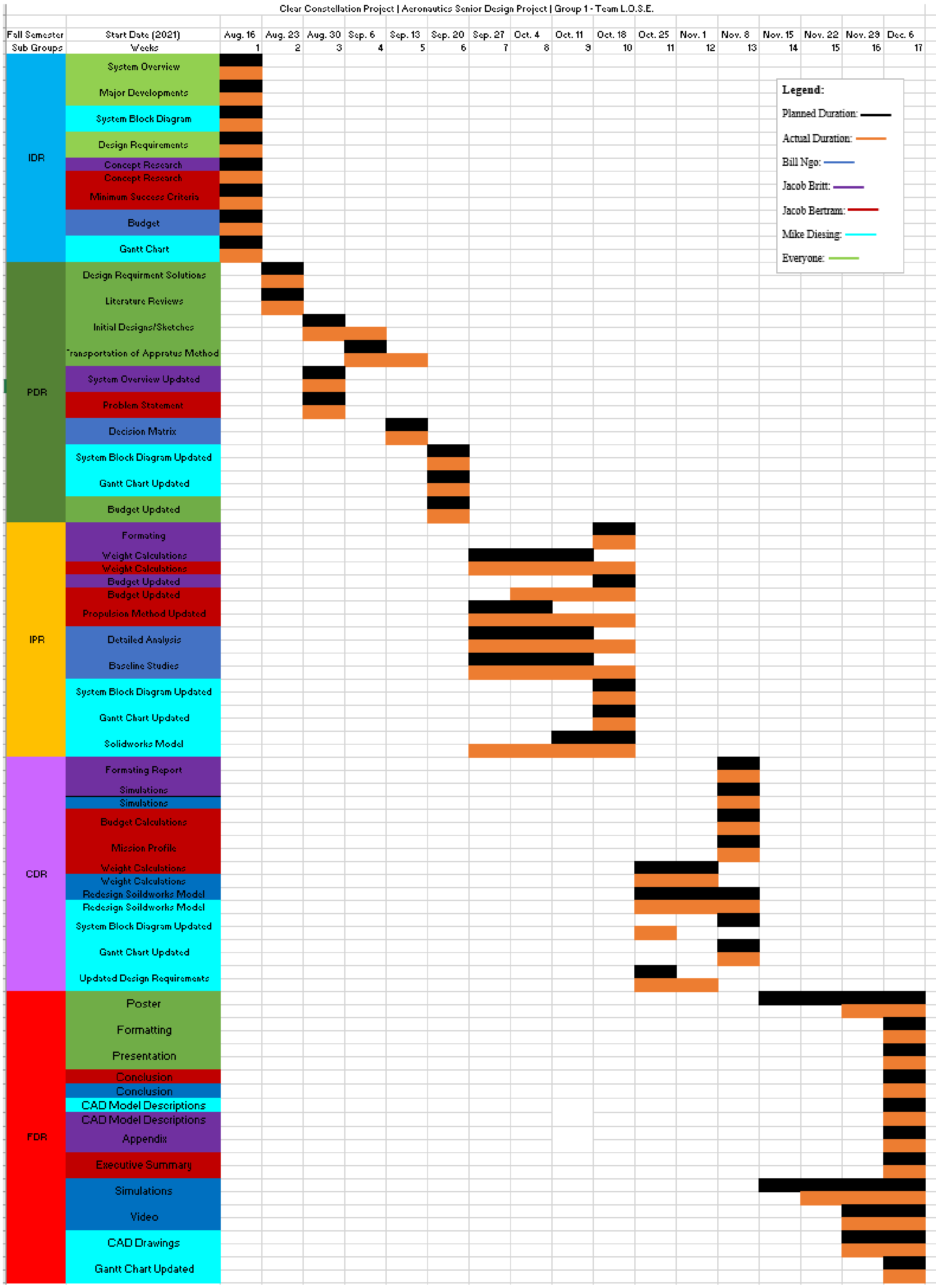


Figure 3: Gantt Chart

3.8 Available and Required Resources (Software, Hardware)

3.8.1 Software

- CAD
- SolidWorks
- Microsoft Office
- Space-Tracking

3.9 Design Approach

The following design, Figure 4: Initial Design Concept 1, takes a more passive approach to collecting debris, and specifically targets debris of sizes less than 10 cm in diameter. Instead of having Scrappie being manually controlled and constantly monitored to collect debris, it will instead be sent in a trajectory towards area which are known to contain debris. Once on its course, Scrappie will be left to idle in orbit and collide with any debris on its path. The design implements a shielding method known as Whipple shielding [26] to collect debris. The Whipple shielding will take advantage of the debris' velocity to break it into smaller pieces. Upon impact with the face of the shield, small to medium sized debris will be vaporized and collected within Scrappie, which can be seen on Figures 5, 6, and 7. However, this design should include appropriate thruster capabilities in order to make up for lost momentum upon impact with debris as well as avoiding large debris that the shield would be unable to handle if it is to maintain orbit. This initial design proposes the use of magnetic coil propulsion [18], however, upon further research it is concluded that this will not be a sufficient propulsion method.

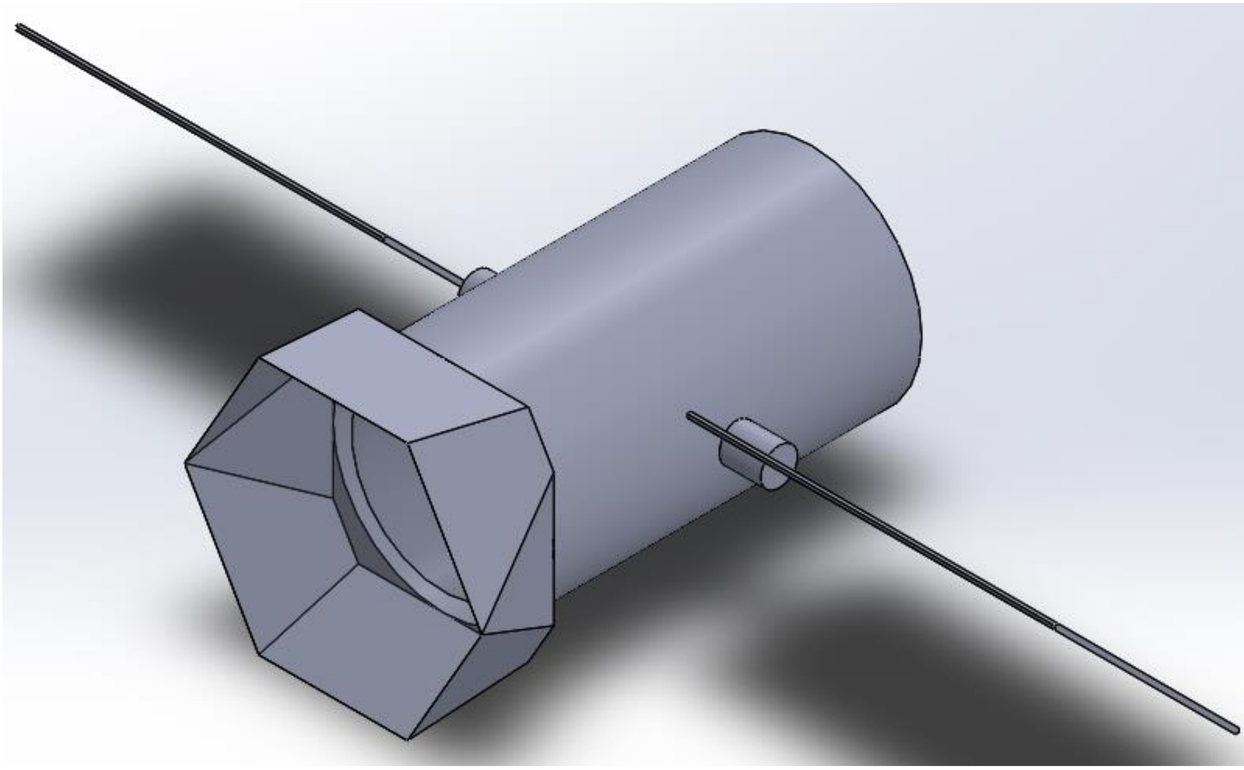


Figure 4: Initial Design Concept 1

Figure 5: Whipple Shield Before Impact

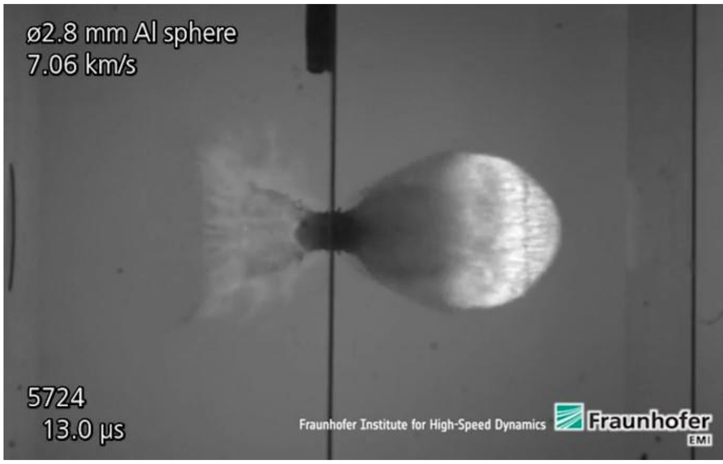


Figure 6: Whipple Shield 13 µs After Impact

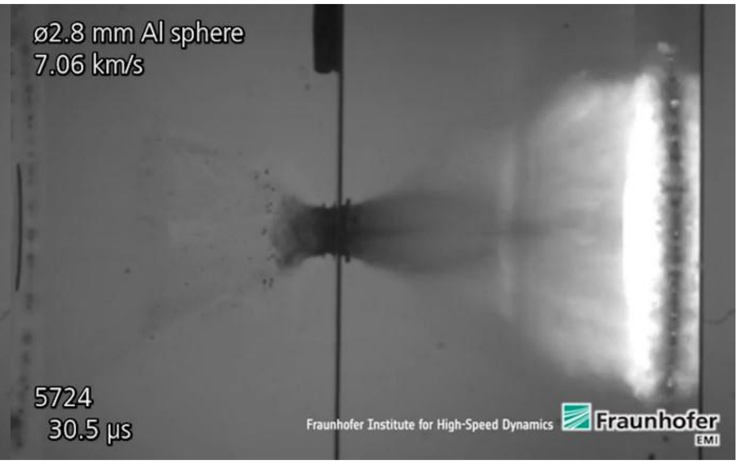


Figure 7: Whipple Shield 30.5 µs After Impact

The design shown below is the Initial Design Concept 2, Figure 8. With its cylindrical shape, this concept uses a netting apparatus and robotic arm to collect oncoming debris. This design was to allow for differentiating between two types of debris collected: useless/trash debris and debris for research. The robotic arm would be able to extend and collect debris desired for research from within the netting and put it within the secondary holding compartment located on the lower half of the apparatus. The other debris would be collected through an opening at the top in the center of the netting. Where it would be store within the main holding compartment on the top half of the apparatus. There is also a panel of solar cells that runs the length and width of the apparatus to support the electronic systems. For maneuvering, this design was going to use two main thrusters on the bottom and positioning thrusters at the top. This design was purposed to be able to dock at the ISS and unload its compartments before starting another mission.

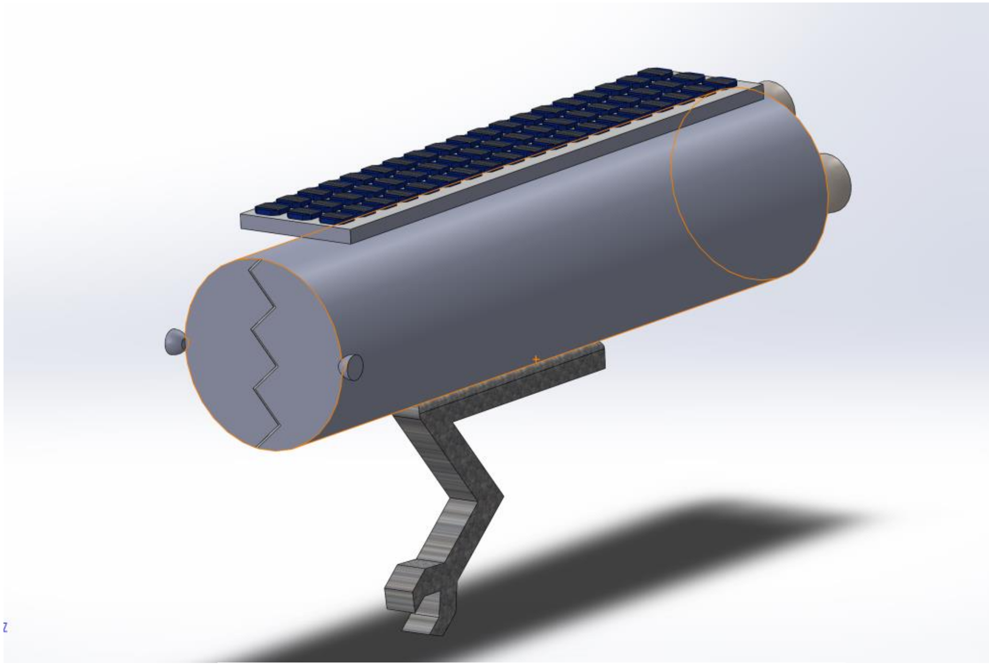


Figure 8: Initial Design Concept 2

3.10 Decision Matrix

In these design matrices, numerous techniques and ideas were brought to the table to allow for different design processes to be considered. In Figures 9 and 10, a TOPSIS decision matrix was formed to determine the best/most efficient method of collection and propulsion system. Each category (cost, efficiency, storage capacity, ease of operation collection, ease of maintenance, availability, reusability, and maneuverability) was given a weight of importance for the apparatus we wanted to create. For the method of collection, we decided that efficiency was the most crucial factor when deciding on how the debris was distributed or captured. Out of the four methods of collection, Whipple shielding came in second. More on our team's reasoning for choosing Whipple shielding is below. These weights continued for each category following with ease of operation, reusability, and maneuverability followed with cost, storage capacity, and ease of maintenance. Lastly, availability was the category we gave the lowest weight to as method of collection was a vastly wide idea that has numerous answers for. As a result, we found that Whipple shielding, and storage were the highest rated methods of collection with storage reaching .01299 higher than Whipple shielding as shown in Figure 11.

The method of propulsion was also included in the TOPSIS matrices in order to determine the best way to allow this apparatus to be powered. The weight of these categories was slightly different than the weights of the method of collection. Rightfully so, efficiency was the highest rated with ease of maintenance and reusability following. We believed having a high rating for efficiency was important as it allowed the decision of the propulsion method to last the longest while also producing the most power. When looking at the matrix, it was decided that the magnetic coil propulsion method was the least efficient because of the use of the magnetic field for operation. After the weights for each category were established, it was determined that the grided electric ion thrusters were the best choice for the matrix we conducted as shown in Figure 11.

Upon analysis of each category (collection and propulsion), it was decided that the onboard storage for the method of collection and the grided electric ion thrusters for the method of propulsion outlasted the other methods. After seeing the results concluded with the weights given, we decided to go away from the storage method and to pursue the method of Whipple shielding. This was decided as a team because of the uniqueness that follows with Whipple shielding. The idea of destroying the debris by making use of Scrappie's momentum seemed to be a more applicable use of idle and automatic collection/destruction of debris. The Whipple Shielding method is something that scientists are not particularly exploring so we believed taking this another step and making an apparatus out of it would set us apart from other debris removal methods.

	Cost	Efficiency	Storage Capacity	Ease of Operation Collection	Ease of Maintainence	Availability	Reusability	Maneuverability
Method of Collection	0.1	0.2	0.1	0.15	0.1	0.05	0.15	0.15
Storage	5	7	7	5	6	5	6	6
Arms/Netting	5	3	3	6	5	5	6	6
Netting	3	4	3	7	6	5	6	6
Idle/Wipple Shielding	7	6	8	6	4	5	5	6
sum of square	108	110	131	146	113	100	133	144
sqrt sum of square	10.39230485	10.48808848	11.44552314	12.08304597	10.63014581	10	11.53256259	12
Method of Propulsion	0.1	0.2	0.1	0.1	0.15	0.1	0.15	0.1
Magnetic Coil	4	4	5	3	7	5	8	4
SuperDraco	8	5	1	8	4	4	8	8
Traditional Thrusters(arcjet)	7	5	2	7	3	7	8	7
Magnetoplasmadynamic	6	5	8	8	8	7	8	7
Gridded Electrostatic Ion	6	7	6	8	8	7	8	8
sum of square	201	140	130	250	202	188	320	242
sqrt sum of square	14.17744688	11.83215957	11.40175425	15.8113883	14.2126704	13.7113092	17.88854382	15.55634919
Nondimensionalize								
	Cost	Efficiency	Storage Capacity	Ease of Operation Collection	Ease of Maintainence	Availability	Reusability	Maneuverability
Method of Collection								
Storage	0.481125224	0.667423812	0.61159284	0.413802944	0.564432521	0.5	0.520265982	0.5
Arms/Netting	0.481125224	0.286038777	0.262111217	0.496563533	0.470360434	0.5	0.520265982	0.5
Netting	0.288675135	0.381385036	0.262111217	0.579324122	0.564432521	0.5	0.520265982	0.5
Idle/Wipple Shielding	0.673575314	0.572077554	0.698963245	0.496563533	0.376288347	0.5	0.433554985	0.5
Method of Propulsion								
Magnetic Coil	0.282138246	0.338061702	0.43852901	0.18973666	0.492518281	0.36466248	0.447213595	0.257129739
SuperDraco	0.564276493	0.422577127	0.087705802	0.505964426	0.281439018	0.29172998	0.447213595	0.514259477
Traditional Thrusters(arcjet)	0.493741931	0.422577127	0.175411604	0.442718872	0.211079263	0.51052747	0.447213595	0.449977043
Magnetoplasmadynamic	0.42320737	0.422577127	0.701646415	0.505964426	0.562878036	0.51052747	0.447213595	0.449977043
Gridded Electrostatic Ion	0.42320737	0.591607978	0.526234812	0.505964426	0.562878036	0.51052747	0.447213595	0.514259477
Weighted	Min	Max	Max	Max	Max	Max	Max	Max
	Cost	Efficiency	Storage Capacity	Ease of Operation Collection	Ease of Maintainence	Availability	Reusability	Maneuverability
Method of Collection	0.1	0.2	0.1	0.15	0.1	0.05	0.15	0.15
Storage	0.048112522	0.133484762	0.061159284	0.062070442	0.056443252	0.025	0.078039897	0.075
Arms/Netting	0.048112522	0.057207755	0.026211122	0.07448453	0.047036043	0.025	0.078039897	0.075
Netting	0.028867513	0.076277007	0.026211122	0.086898618	0.056443252	0.025	0.078039897	0.075
Idle/Wipple Shielding	0.067357531	0.114415511	0.069896325	0.07448453	0.037628835	0.025	0.065033248	0.075
Method of Propulsion	0.1	0.2	0.1	0.1	0.15	0.1	0.15	0.1
Magnetic Coil	0.028213825	0.06761234	0.043852901	0.018973666	0.073877742	0.03646625	0.067082039	0.025712974
SuperDraco	0.056427649	0.084515425	0.00877058	0.050596443	0.042215853	0.029173	0.067082039	0.051425948
Traditional Thrusters(arcjet)	0.049374193	0.084515425	0.01754116	0.044271887	0.03166189	0.05105275	0.067082039	0.044997704
Magnetoplasmadynamic	0.042320737	0.084515425	0.070164642	0.050596443	0.084431705	0.05105275	0.067082039	0.044997704
Gridded Electrostatic Ion	0.042320737	0.118321596	0.052623481	0.050596443	0.084431705	0.05105275	0.067082039	0.051425948

Figure 9: Decision Matrix TOPSIS 1

Positive Ideal								
	Cost	Efficiency	Storage Capacity	Ease of Operation Collection	Ease of Maintainence	Availability	Reusability	Maneuverability
Method of Collection	0.067357531	0.133484762	0.069896325	0.086898618	0.056443252	0.025	0.078039897	0.075
Method of Propulsion	0.056427649	0.118321596	0.070164642	0.050596443	0.084431705	0.05105275	0.067082039	0.051425948
Negative Ideal								
	Cost	Efficiency	Storage Capacity	Ease of Operation Collection	Ease of Maintainence	Availability	Reusability	Maneuverability
Method of Collection	0.028867513	0.057207755	0.026211122	0.062070442	0.037628835	0.025	0.065033248	0.075
Method of Propulsion	0.028213825	0.06761234	0.00877058	0.018973666	0.03166189	0.029173	0.067082039	0.025712974
Euclidean Distance Positive								
	Cost	Efficiency	Storage Capacity	Ease of Operation Collection	Ease of Maintainence	Availability	Reusability	Maneuverability
Method of Collection								
Storage	0.00037037	0	7.63359E-05	0.000616438	0	0	0	0
Arms/Netting	0.00037037	0.005818182	0.001908397	0.00015411	8.84956E-05	0	0	0
Netting	0.001481481	0.003272727	0.001908397	0	0	0	0	0
Idle/Wipple Shielding	0	0.000363636	0	0.00015411	0.000353982	0	0.000169173	0
Method of Propulsion								
Magnetic Coil	0.00079602	0.002571429	0.000692308	0.001	0.000111386	0.00021277	0	0.000661157
SuperDraco	0	0.001142857	0.003769231	0	0.001782178	0.00047872	0	0
Traditional Thrusters(arcjet)	4.97512E-05	0.001142857	0.002769231	0.00004	0.002784653	0	0	4.13223E-05
Magnetoplasmadynamic	0.000199005	0.001142857	0	0	0	0	0	4.13223E-05
Gridded Electrostatic Ion	0.000199005	0	0.000307692	0	0	0	0	0
Euclidean Distance Negative								
	Cost	Efficiency	Storage Capacity	Ease of Operation Collection	Ease of Maintainence	Availability	Reusability	Maneuverability
Method of Collection								
Storage	0.00037037	0.005818182	0.001221374	0	0.000353982	0	0.000169173	0
Arms/Netting	0.00037037	0	0	0.00015411	8.84956E-05	0	0.000169173	0
Netting	0	0.000363636	0	0.000616438	0.000353982	0	0.000169173	0
Idle/Wipple Shielding	0.001481481	0.003272727	0.001908397	0.00015411	0	0	0	0
Method of Propulsion								
Magnetic Coil	0	0	0.001230769	0	0.001782178	5.3191E-05	0	0
SuperDraco	0.00079602	0.000285714	0	0.001	0.000111386	0	0	0.000661157
Traditional Thrusters(arcjet)	0.000447761	0.000285714	7.69231E-05	0.00064	0	0.00047872	0	0.000371901
Magnetoplasmadynamic	0.000199005	0.000285714	0.003769231	0.001	0.002784653	0.00047872	0	0.000371901
Gridded Electrostatic Ion	0.000199005	0.002571429	0.001923077	0.001	0.002784653	0.00047872	0	0.000661157

Figure 10: Decision Matrix TOPSIS 2

Method of Collection	S+	S-
Storage	0.032605898	0.089067848
Arms/Netting	0.09132116	0.027966917
Netting	0.081624786	0.03877151
Idle/Wipple Shielding	0.032263	0.082563402
Method of Propulsion		
Magnetic Coil	0.077750018	0.055372727
SuperDraco	0.084693503	0.053425437
Traditional Thrusters(arcjet)	0.082630593	0.047968977
Magnetoplasmadynamic	0.037191188	0.094282701
Gridded Electrostatic Ion	0.022509937	0.098071629
Relative Closeness		
Method of Collection		
Storage	0.732021908	
Arms/Netting	0.234448555	
Netting	0.322032413	
Idle/Wipple Shielding	0.719028031	
Method of Propulsion		
Magnetic Coil	0.415952415	
SuperDraco	0.386807465	
Traditional Thrusters(arcjet)	0.367298125	
Magnetoplasmadynamic	0.717121111	
Gridded Electrostatic Ion	0.813321902	

Figure 11: Decision Matrix TOPSIS Results

3.11 SolidWorks Model

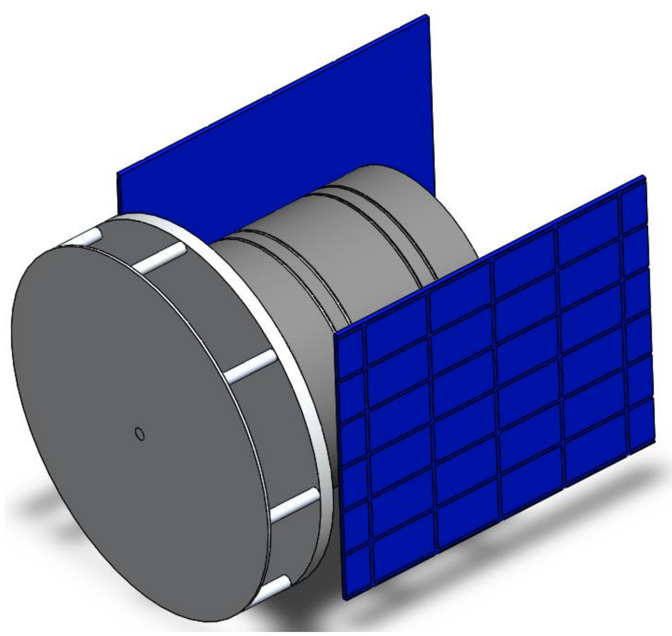


Figure 12: Scrappie Isometric View

Figure 12 is a 3D CAD model of Scrappie in an isometric view. Scrappie consists of 3 separate parts: a hull, solar arrays, and a Whipple Shield. Scrappie is mostly made out of Aluminum 2024 but does contain a few other materials like Kevlar which is used in the Whipple Shield and Xenon, the thruster's propellant, stored in the hull. Scrappie's Whipple Shield acts like a collecting guard, not only protecting Scrappie's hull and solar arrays from particles, but also collecting the particles that are 10 cm or less in which it'll come in contact with. Scrappie's solar arrays will provide the electrical components with the amount of electricity needed rotating around the hull on a track system. Scrappie will use three Gridded Electrostatic Ion thrusters to keep along the debris path and provide enough force to collect particles of 10 cm or less.

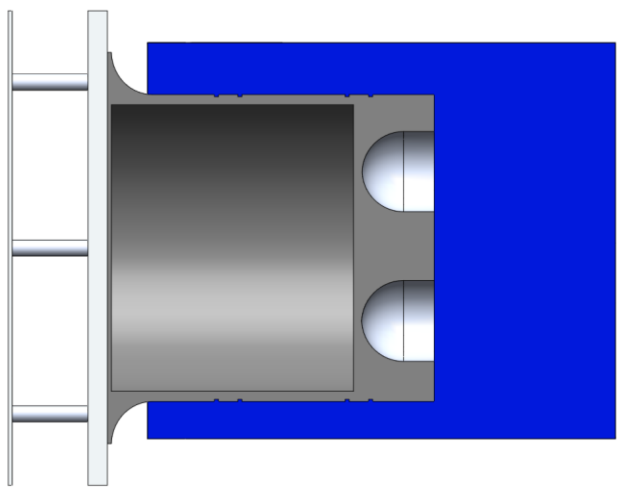


Figure 13: Scrappie Section View

Figure 13 is a section view of Scrappie. It provides a look into where the thrusters would be stored, along with its propellant and electrical components. It also shows how the hull is connected to the Whipple Shield, along with the protective casing separating each part. The isometric and section views for each modeled part is located in Appendix A.

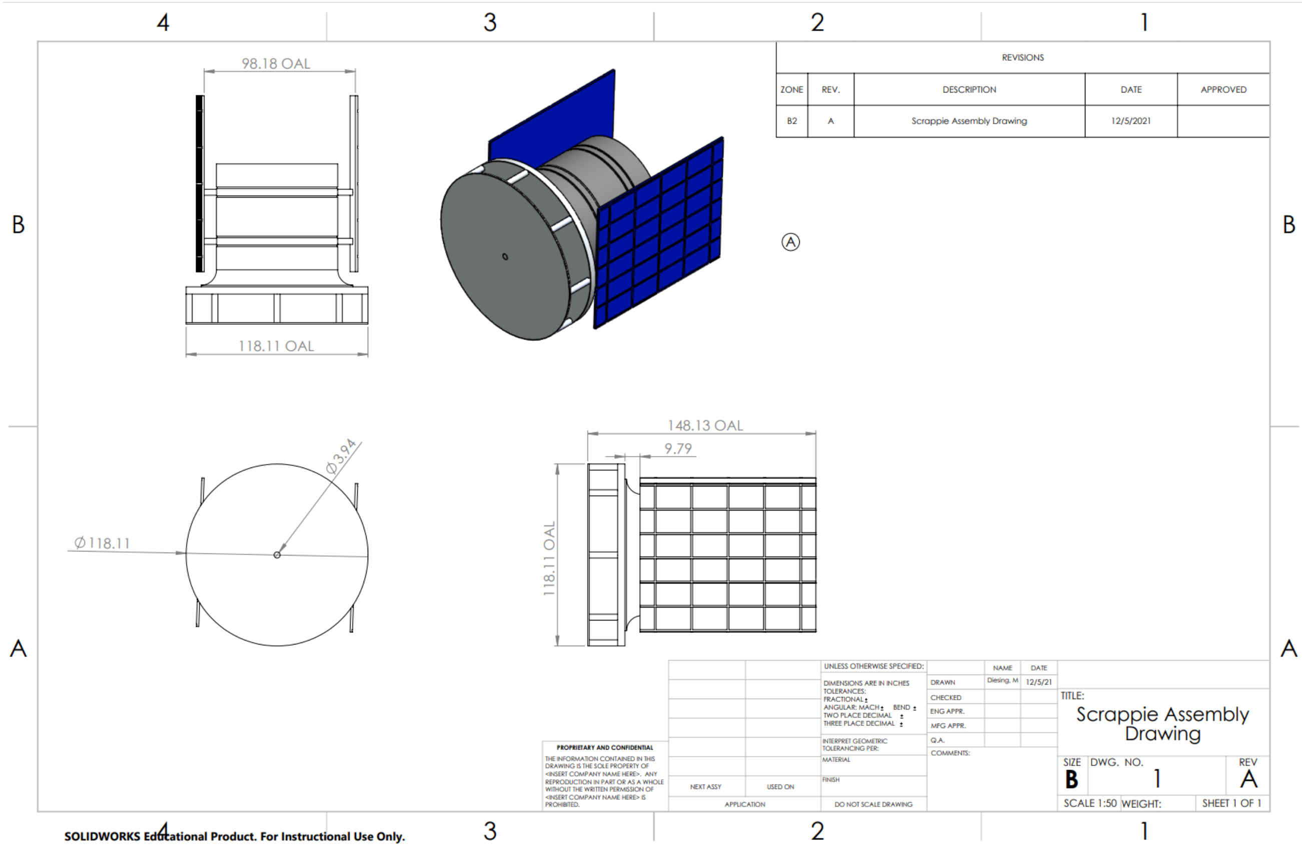


Figure 14: Scrappie Assembly Drawing

Figure 14 is Scrappie's assembly drawing. It provides the overall dimensions of Scrappie. Utilizing the information from the drawing, it proves that Scrappie that it can fit inside the Falcon Heavy of Ariane's 5 cargo space as a full assembly. The drawing for each modeled part is located in Appendix B.

4.0 Simulation Results and Analysis

4.1 10-cm Debris Impact Simulation

An impact simulation was performed in SolidWorks on a 10 cm diameter aluminum sphere. The results of this simulation were used to define the total time interval of debris impact with the face of the Whipple Shield. The 10 cm projectile will be simulated to impact a rigid plane at 10.0 km/s.

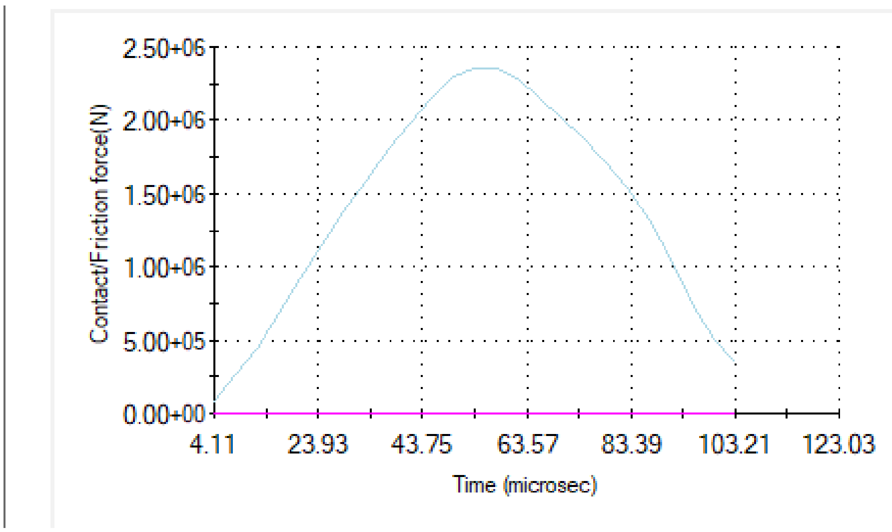


Figure 15: Debris Impact Response - Contact Force vs Time

It can be seen in Figure 14 that the impact of debris onto the Whipple Shield occurs over an interval of 103 microseconds. This time interval will be used in a nonlinear dynamic simulation between the 10 cm projectile and Scrappie's full assembly.

4.2 Nonlinear Dynamic Impact Simulation

A nonlinear dynamic study was utilized to simulate the impact of debris with Scrappie. The size of debris will be a 10 cm diameter aluminum sphere, and it will have an impact velocity of 10.0 km/s. The craft will also have an impact velocity of equal magnitude and opposite in direction. These parameters are meant to be the upper limits of Scrappie's design requirements.

The time interval of this impact will occur over a 103-microsecond interval, as mentioned in section 4.1. The point of impact will be set at the center of the bumper plate.

Similar simulations were performed with different points of impact in mind, such as the midpoint between the center and edge of the bumper plate, edge of the bumper plate, and impact on the face where a supporting rod is found. These simulations yielded similar results (see Appendix C).

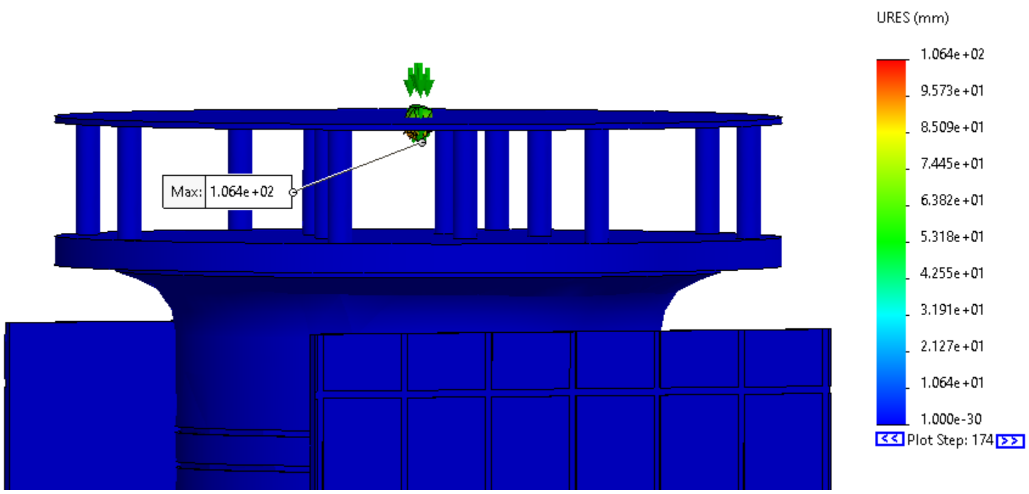


Figure 16: Nonlinear Dynamic Impact Results - Displacement

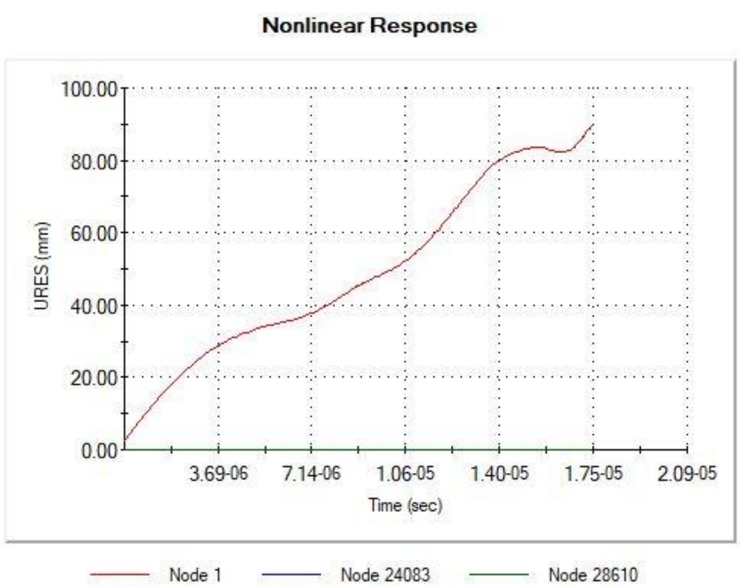


Figure 17: Nonlinear Dynamic Response - Displacement vs Time

The displacement responses at specific points of the assembly were then plotted as a function of time. Node 1 is located on the bumper face at the point of impact, Node 24083 is displaced radially 5 cm away from Node 1, and Node 28610 is located on the back wall directly behind Node 1. As seen in Figures 15 and 16, Node 1 experiences a displacement (~90 cm) that is greater than the thickness of the bumper face, which has a thickness of 2.4 cm. Nodes 24083 and 28610 experience no significant displacement. This indicates that the projectile (debris) successfully penetrates the bumper plate without sustaining damage to any other parts of the craft.

In actual application, the projectile would be vaporized due to its high velocity upon impact with the bumper plate. Once vaporized, it will be collected by the Kevlar stuffing installed between the bumper plate and back wall.

4.3 Shock Response Simulation

During launch, the payload fairing will be subject to different shock values at various stages of launch. According to the Falcon Heavy user guide, there are four events during launch that are classified as shock loads. Stage 1 is vehicle lift off, stage 2 is 2nd stage separation, stage 3 is payload fairing separation, and stage 4 is payload release.

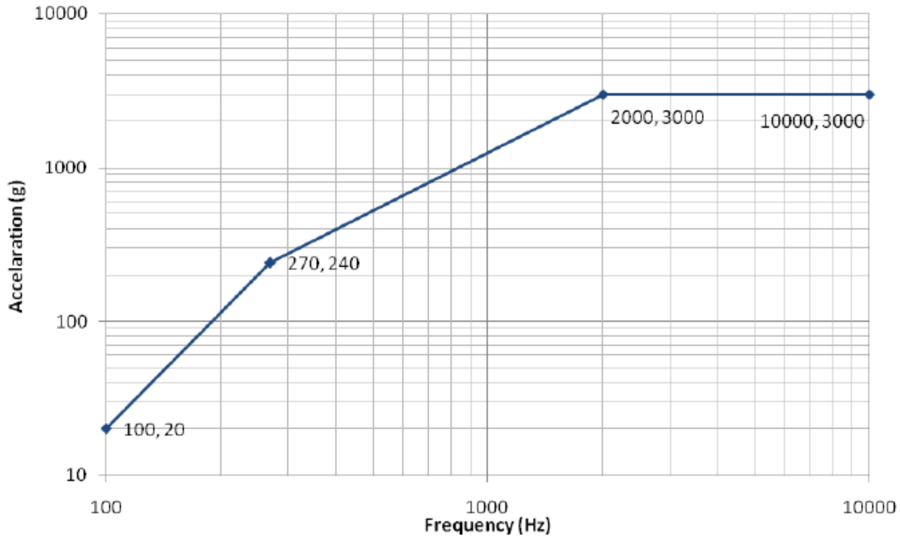


Figure 18: Falcon Heavy Shock Response at Payload Fairing

From Figure 17, the acceleration of the vehicle is given as a function of frequency. The nodes represent the four shock events during launch. The data on this plot will give a value for jerk in $\frac{m}{s^3}$. Integration of the jerk value over the time interval of each stage during launch will result in a shock load value in $\frac{m}{s^2}$.

At stage 1 the payload fairing will experience 5 Gs, where 1 G is equivalent to normal acceleration due to gravity (9.81 $\frac{m}{s^2}$). At state 2 the payload fairing will experience a shock load of 1.125 Gs, state 3 will see 0.667 Gs, and state 4 will see 3.33 Gs. We will utilize a SolidWorks dynamic study to simulate the maximum shock load experienced during launch, which occurs at state 1.

Scrappie will be assumed to be fixed to the SpaceX payload fairing at the bumper plate, main hull, and solar arrays. Although, the specifics of how the payload is secured onto the payload fairing are decided by SpaceX. A shock load of 5 Gs will be applied through Scrappie's longitudinal axis, opposite to the direction of flight.

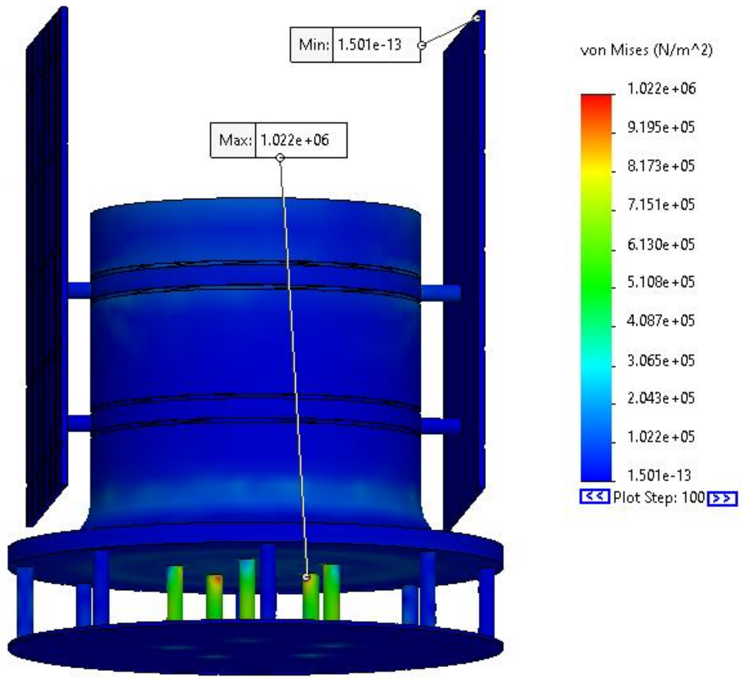


Figure 19: Dynamic 5 G Shock Loading Results - Stress

The results for the shock load simulation, shown in Figure 19, show that Scrappie will experience a maximum stress of 1.02 MPa at the base of the rods that connect the bumper plate to the back wall. The material used for Scrappie's design, AA2024-T4, has a yield strength of 325 MPa. This means that at the maximum stress experienced during launch, the rod will have a factor of safety of 318.

5.0 Conclusion

The growing issue of space debris in Low Earth Orbit is a new and concerning problem. Since it is a newer issue, there are not many projects or missions that can be used to benchmark what a successful design approach would be. Based off the simulations presented in Chapter 4.0, it can be concluded that the design of Scrappie is applicable to accomplishing the targeted mission. This means that Scrappie would be able to clear desired orbital paths for various satellites and spacecrafts. By doing so, these satellites and spacecrafts will have opportunities to orbit without the idea of being interrupted by certain debris. By seeing the simulations carry a high factorization on impact, velocity, and damage, we determined the necessary requirements in material and components to withstand the hazards that may come. With the Whipple Shield and the aluminum alloy material that designed the hull, Scrappie will be able to survive conditions associated with Low Orbit around Earth. The Solar Arrays give the necessary power needed in order to complete various missions without worry about a power outage.

Recommendations are always mentioned for innovation purposes. These include but not limited to:

- Changing the material of the Hull to withstand more pressure, velocities, and temperatures that aluminum 2024 cannot handle. Having the ability to travel to space without the need of a transport vehicle would require Scrappie to have strong enough material to hold up during atmospheric changes.
- Increasing the size of the Hull and thrusters in order to find and deconstruct debris sizes higher than 10 cm. This could decrease the number of mass-produced products that are sent up and used when clearing the path for one satellite or spacecraft.

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Appendix A: Acknowledgements

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Appendix B: Contact Information

Table 6: Contact Information

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Jacob Britt	Student	(678) 502-6471	jpbritt5@yahoo.com
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Adeel Khalid	Advisor	(470) 578-7241	adeel.khalid@kennesaw.edu

Appendix C: Reflections

Appendix C.1: The Educational Experience

The educational experience that this project offered was limitless. Not only did it allow our team to apply our skills learned throughout completing our engineering courses, but it also allowed us to learn the benefits of strong, organized teamwork. By utilizing our skill sets, we were able to accomplish the development of a solution to a real-world problem.

Appendix C.2: Challenges Faced

We ran into plenty of challenges throughout this project. Every design review produced different challenges to us, some expected and some not expected. The most common challenges faced were deciding the overall weight and budget, specific design requirements, and getting the simulations to run with our 3D model.

Appendix C.3: Resolutions

Our solutions for reducing the weight and cost of Scrappie was found in limiting the size of the entire apparatus. This reduction led to a decrease in the weight and cost for the main hull due to not as much aluminum alloy being needed. However, this did require us to rework the propulsion capabilities of Scrappie as the reduction in weight led to an increased displacement from debris collisions. Determining optimal solutions for different design requirements, like providing Scrappie with enough power to perform the targeted missions, were resolved through an exceptional amount of research. Using brand new, top of the line technology to obtain the power Scrappie needed proved to be the best solution. Troubleshooting our 3D modeling required countless attempts to recognize and understand what was causing the issues. Most of the time these ended up being small issues that just required a quick adjustment.

Appendix D: Design Views

Appendix D.1: Hull

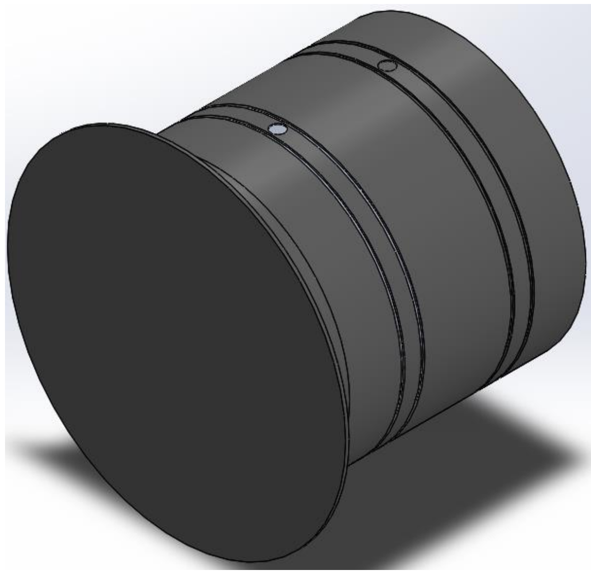

Figure 20: Hull Isometric View

In Figure 20, the Hull of Scrappie is made of Aluminum 2024 and shows the inner shell without the solar arrays attached to it. The two tracks systems that revolve in a circle around the Hull are where the Solar Arrays are going to circle in order to always be facing the sun.

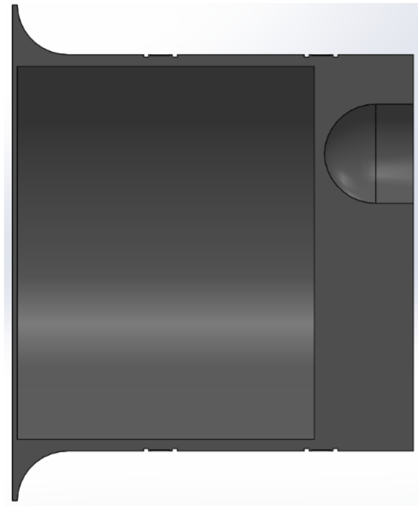

Figure 21: Hull Section View

Figure 21 provides a section view of the Hull. The oval indention on the right side of the figure is where the thrusters are placed and held. The hollow inside of the Hull that is where the propellant will be stored and maintained along with any electrical components.

Appendix D.2: Whipple Shielding

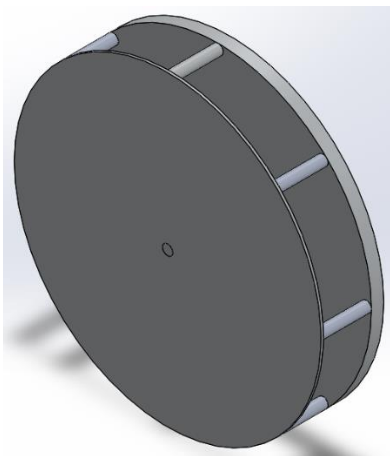

Figure 22: Whipple Shield Isometric View

Figure 22 gives a representation of the Whipple Shield. It shows how each plate is structured and held together as well as show the thickness of the Kevlar layer that will end up catching the debris fragments.

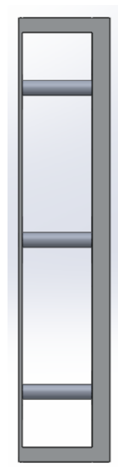

Figure 23: Whipple Shield Section View

This figure, Figure 23, shows the thickness of the Whipple Shield and the supports that attach the back layer and the Kevlar to the front Whipple Shield.

Appendix D.3: Solar Arrays

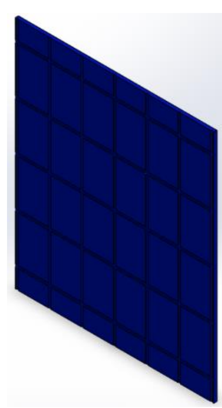

Figure 24: Solar Arrays Isometric View

Figure 24 shows the Solar Array as a whole. It gives representation as to how it is designed with each cell being equal in distance.

Figure 25: Solar Arrays Section View

In this figure, Figure 25, the Solar Array is represented by how it will be attached to the Hull of Scrappie. There are two support beams that will attach to the back of the Solar Arrays and attach to the Hull itself.

Appendix E: Detailed Drawing of Design Layout

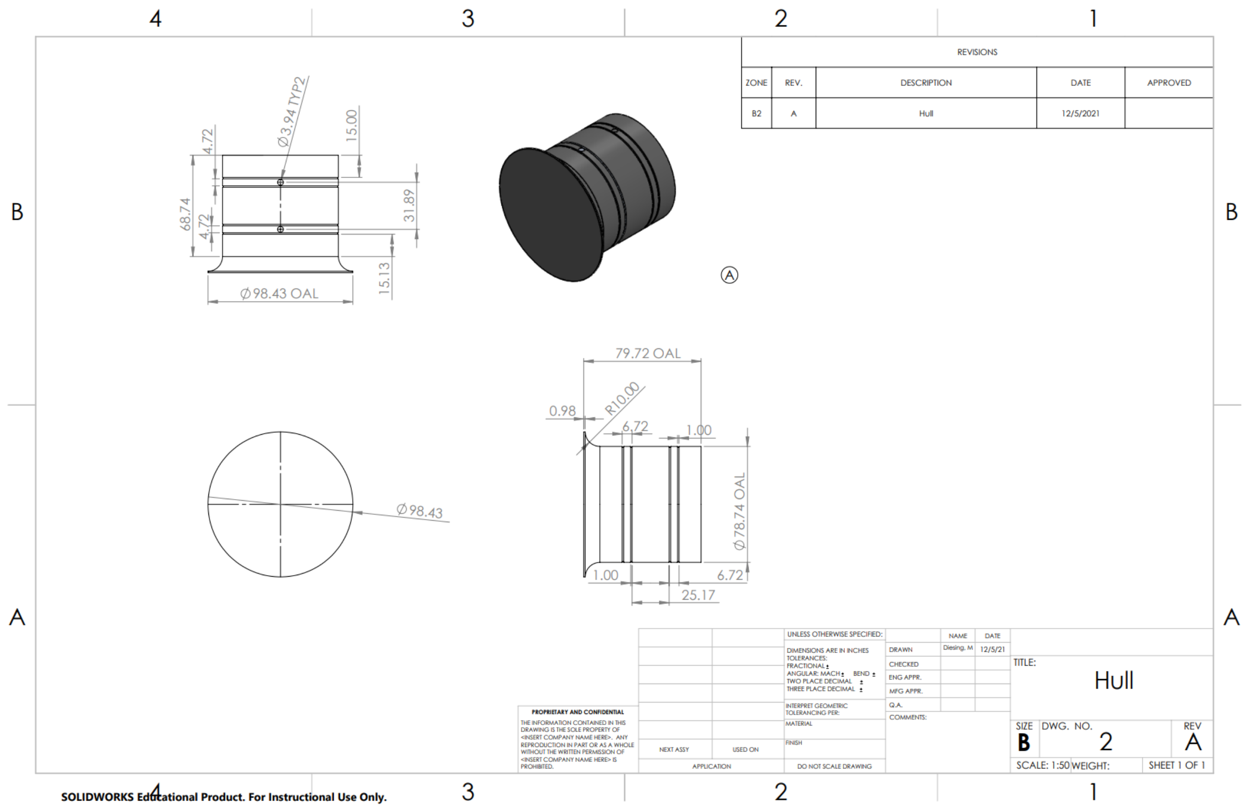

Figure 26: Hull Drawing

Figure 26 is a drawing of the Hull part for Scrappie. The drawing provides the overall lengths and the necessary structural dimensions needed to build the Hull.

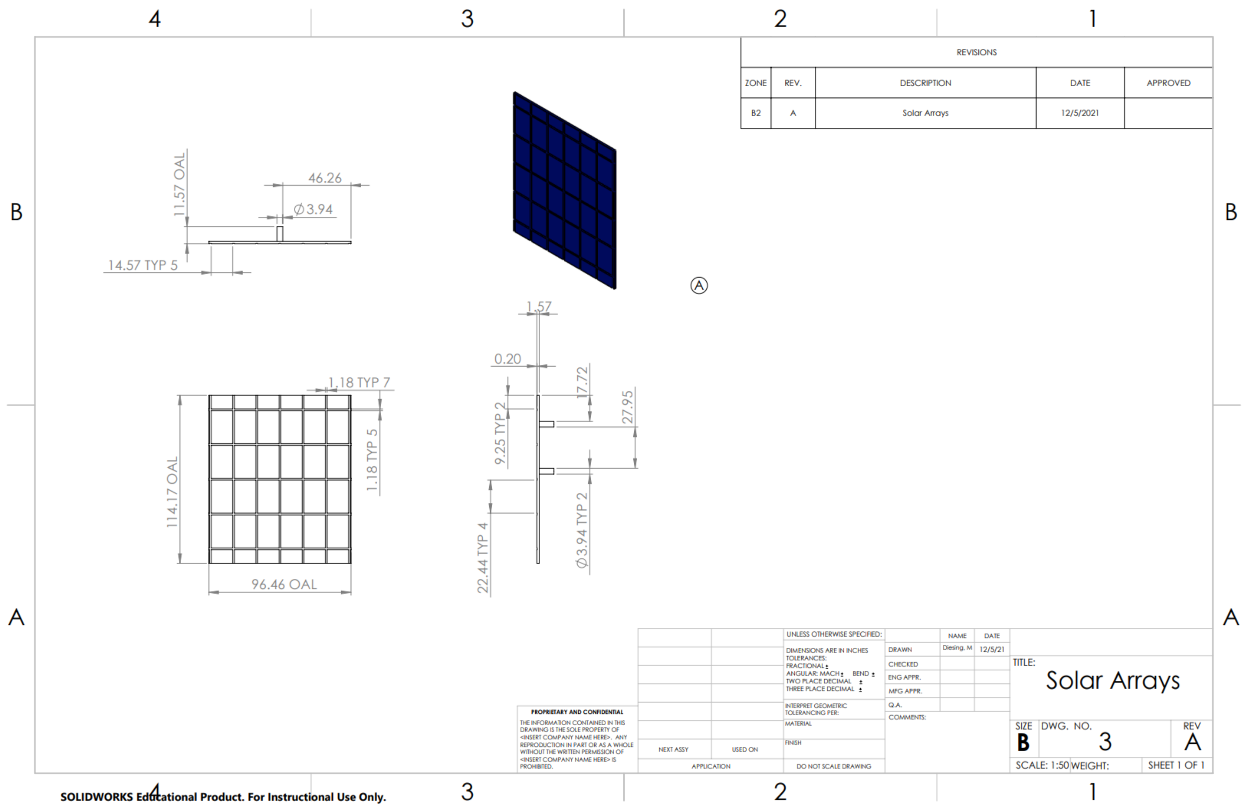

Figure 27: Solar Arrays Drawing

Figure 27 is a drawing of the Solar Arrays part for Scrappie. The drawing provides the overall lengths and the necessary structural dimensions needed to build the Solar Arrays.

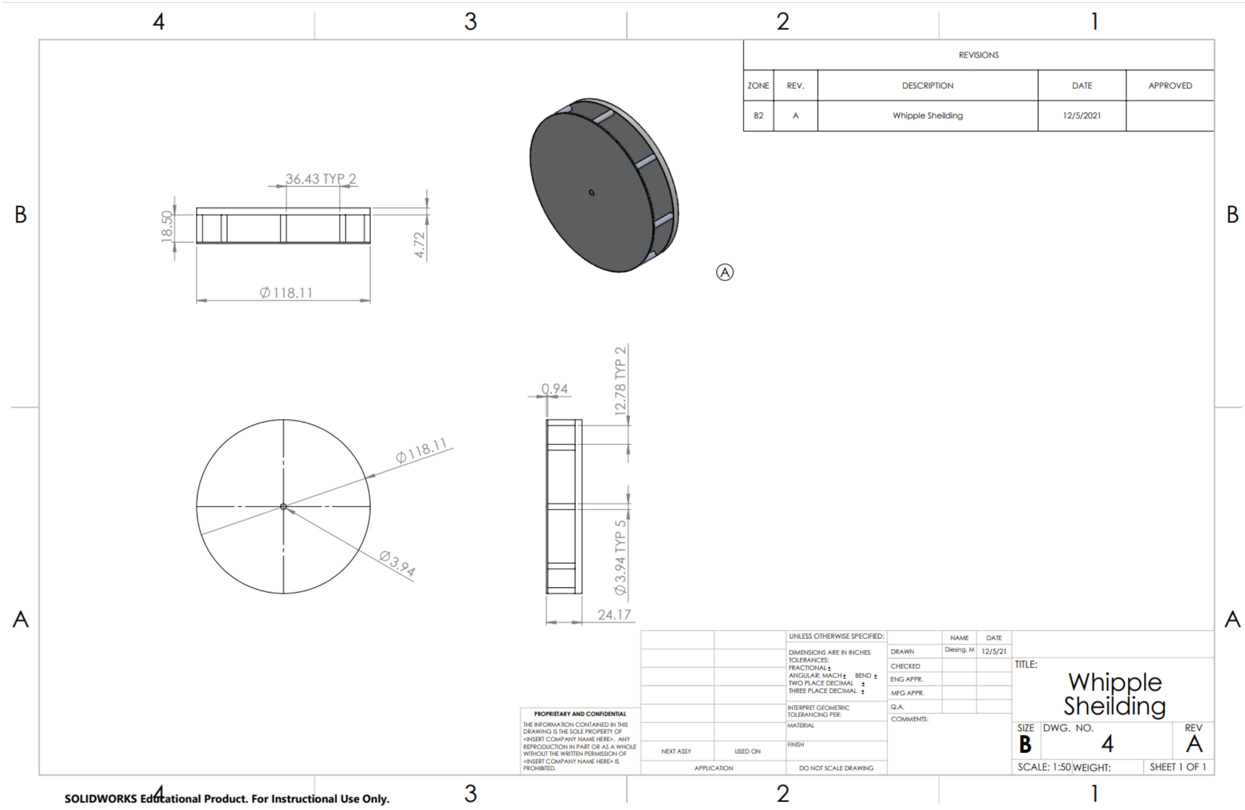

Figure 28: Whipple Shielding Drawing

Figure 28 is a drawing of the Whipple Shielding part for Scrappie. The drawing provides the overall lengths and the necessary structural dimensions needed to build the Whipple Shielding.

Appendix F: SolidWorks Simulations

Appendix F.1: Nonlinear Dynamic Collision Simulations

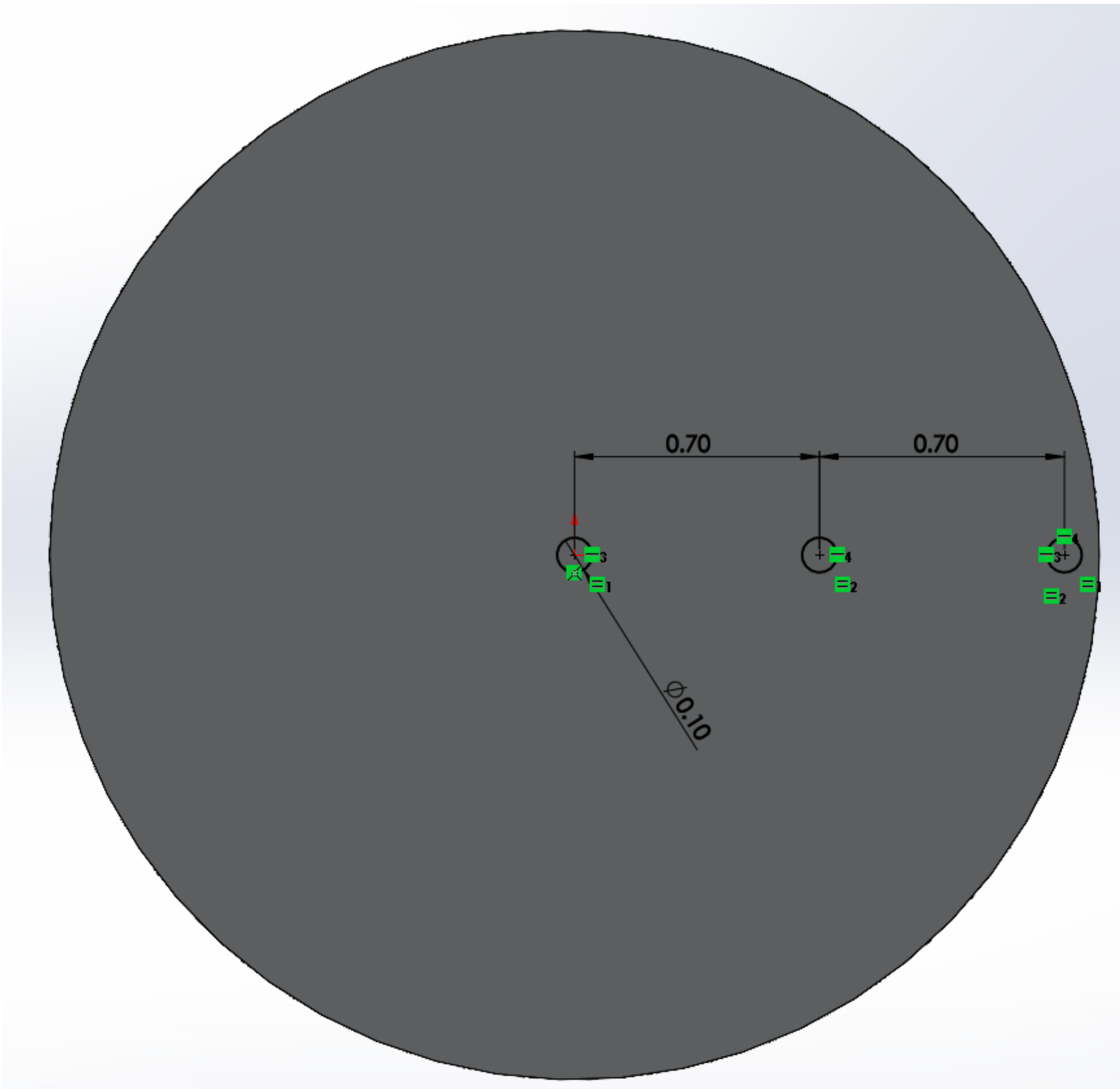

Figure 29: Impact Locations

Figure 29 shows the three locations for impact that will be simulated. Impact 1 refers to the point at the center of the bumper plate. Impact 2 refers to the point 0.70 m away from the center point. Impact 3 refers to the point 1.40 m away from the center point. Impact 3 also impacts a supporting rod that connects the bumper plate to the back wall.

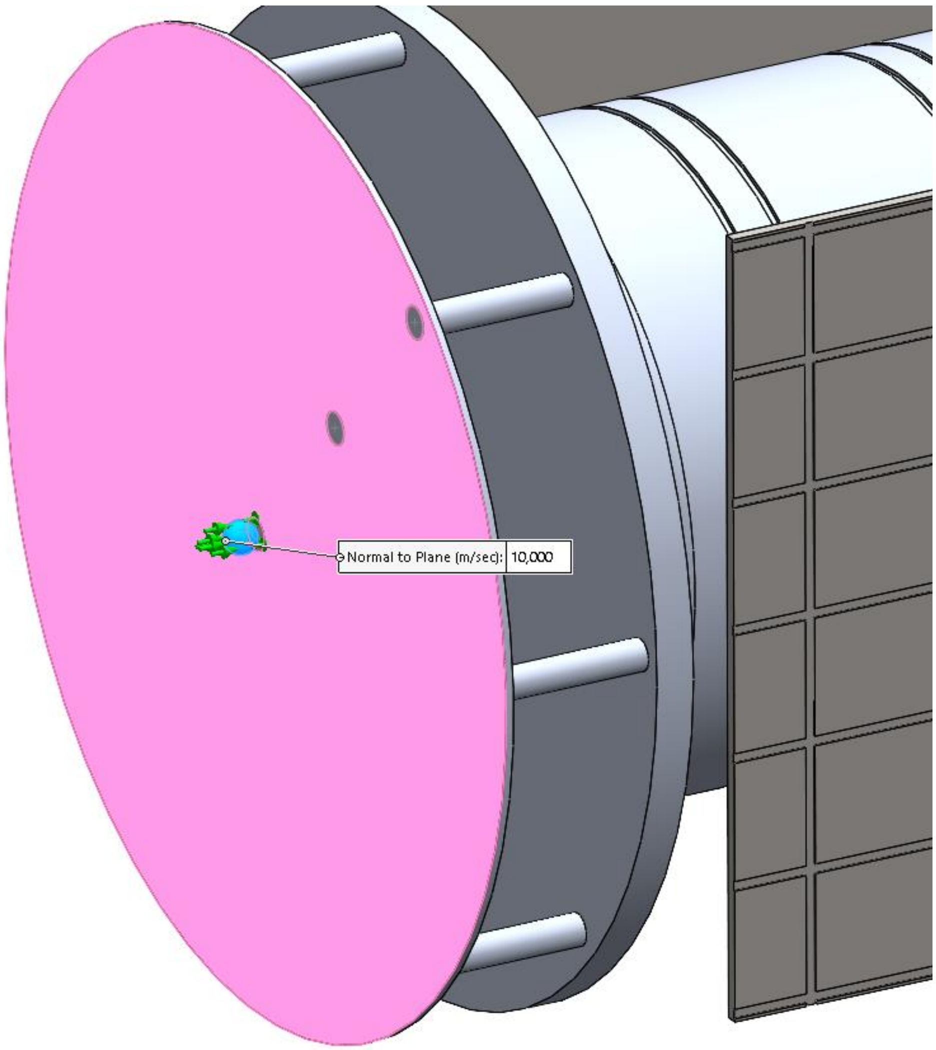

Figure 30: Impact Test 1 Debris Initial Condition

Figure 30 shows the initial conditions of the debris, set at 10.0 km/s, traveling normal to the bumper plate. This impact will occur at the center of the bumper plate.

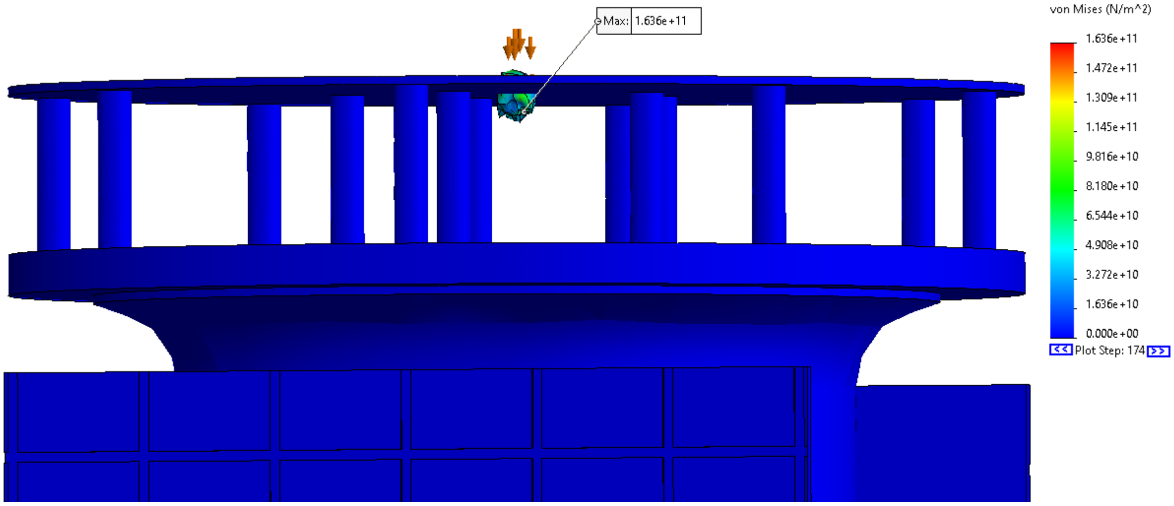

Figure 31: Impact Test 1 Results – Stress

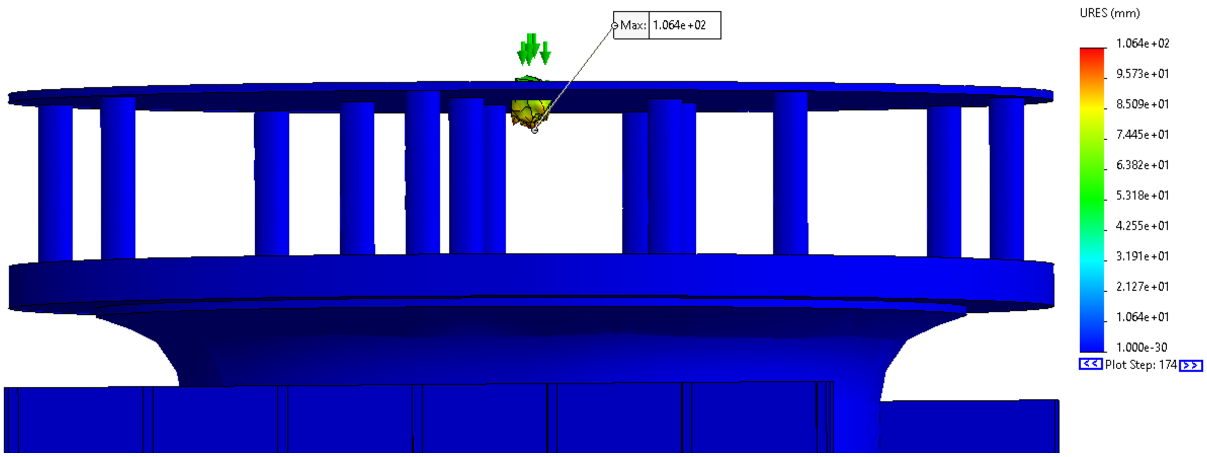

Figure 32: Impact Test 1 Results – Displacement

Figures 31 and 32 shows the resulting stress and displacement of Impact Test 1, respectively. It should be noted that these values are very high and show that the bumper plate fails, however, the failure of the bumper plate is intentional, and is true for all impact test performed.

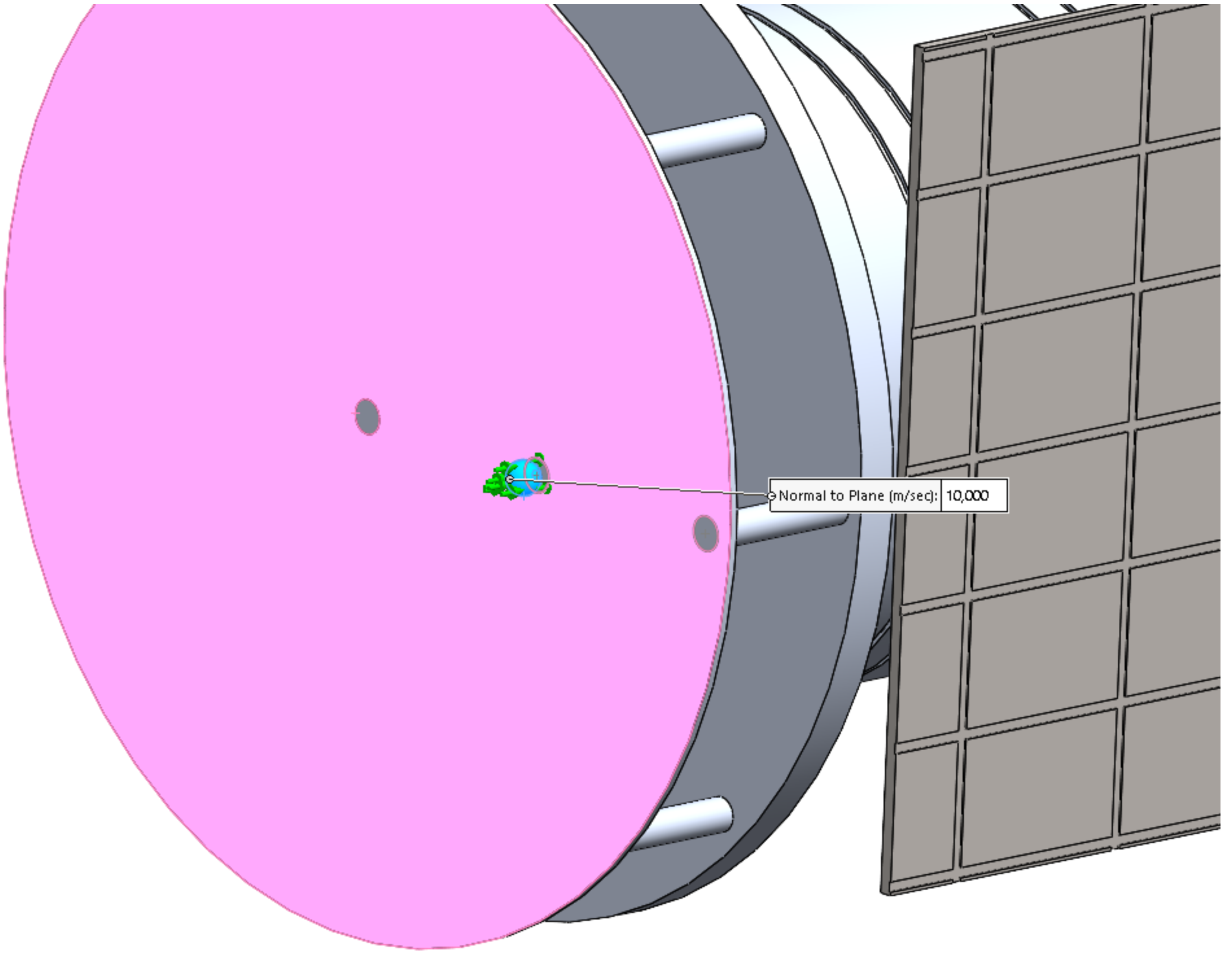

Figure 33: Impact Test 2 Debris Initial Condition

Figure 33 shows the initial conditions of the debris, set at 10.0 km/s traveling normal to the bumper plate. This impact will occur 0.70 m away from the center of the bumper plate.

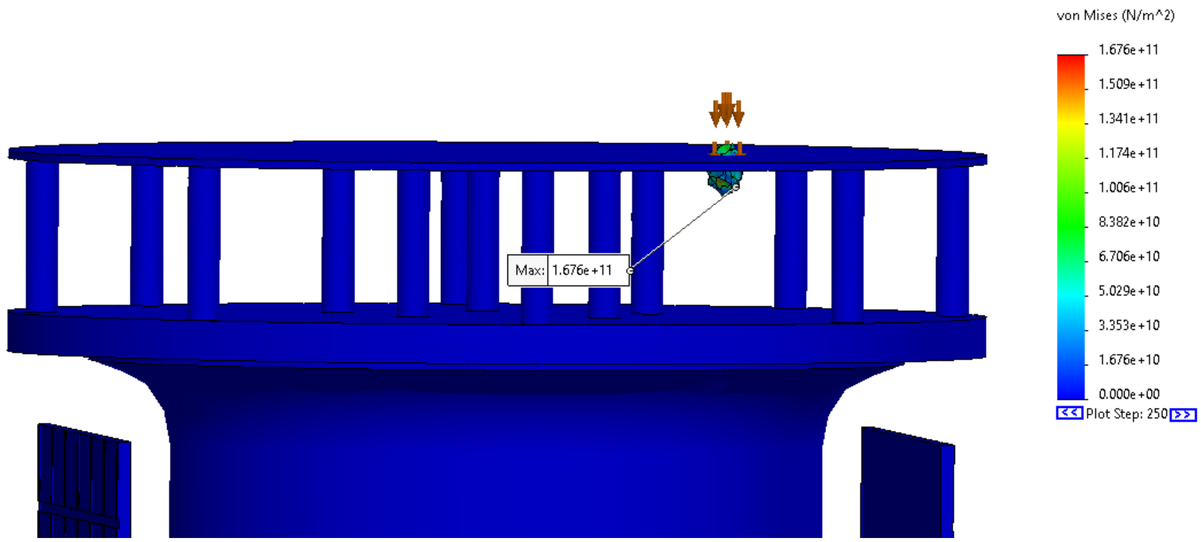

Figure 34: Impact Test 2 Results - Stress

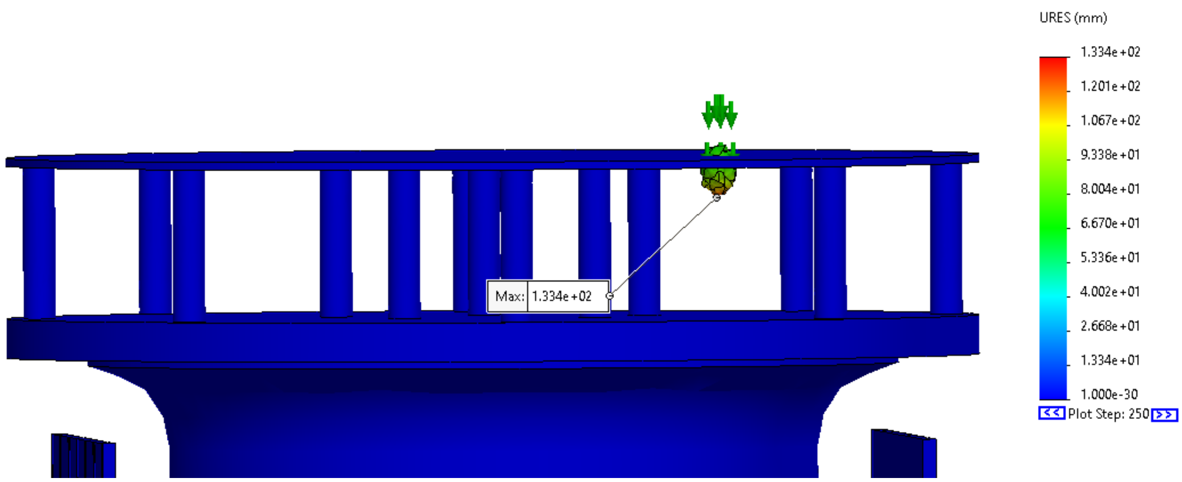

Figure 35: Impact Test 2 Results - Displacement

Figures 34 and 35 shows the resulting stress and displacement of Impact Test 2, respectively.

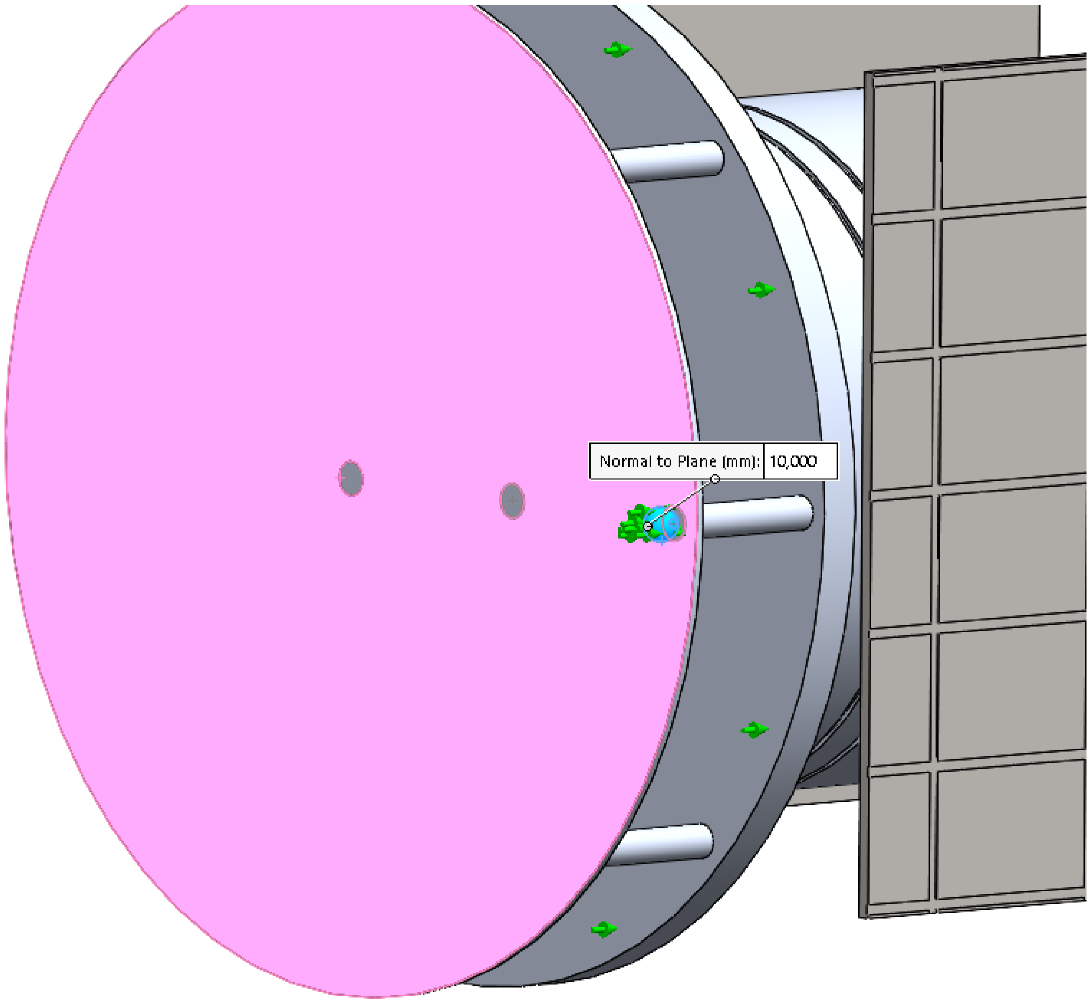

Figure 36: Impact Test 3 Debris Initial Condition

Figure 36 shows the initial conditions of the debris, set at 10.0 km/s traveling normal to the bumper plate. This impact will occur 1.40 m away from the center of the bumper plate and will also strike a supporting rod.

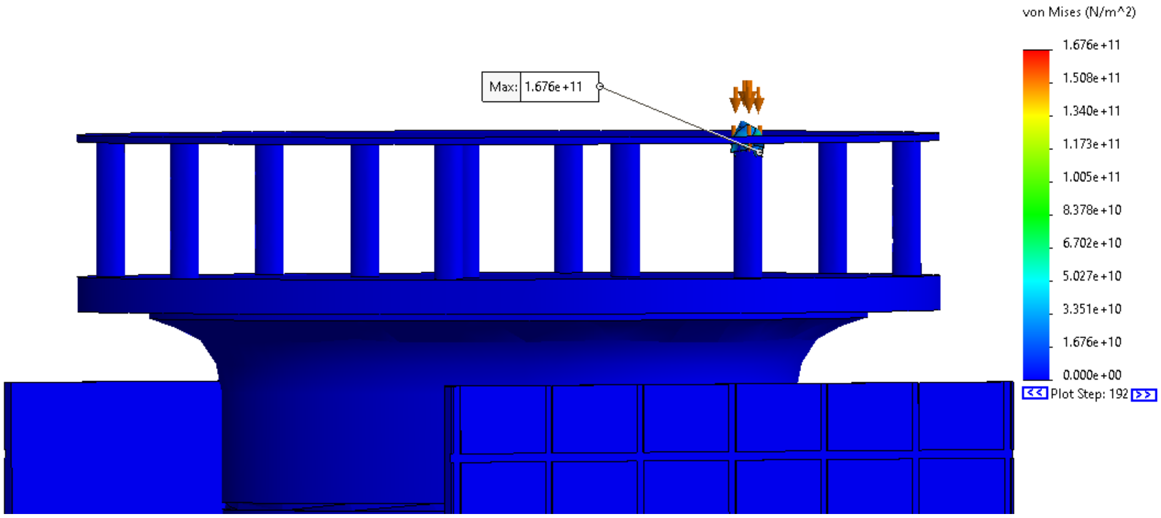

Figure 37: Impact Test 3 Results - Stress

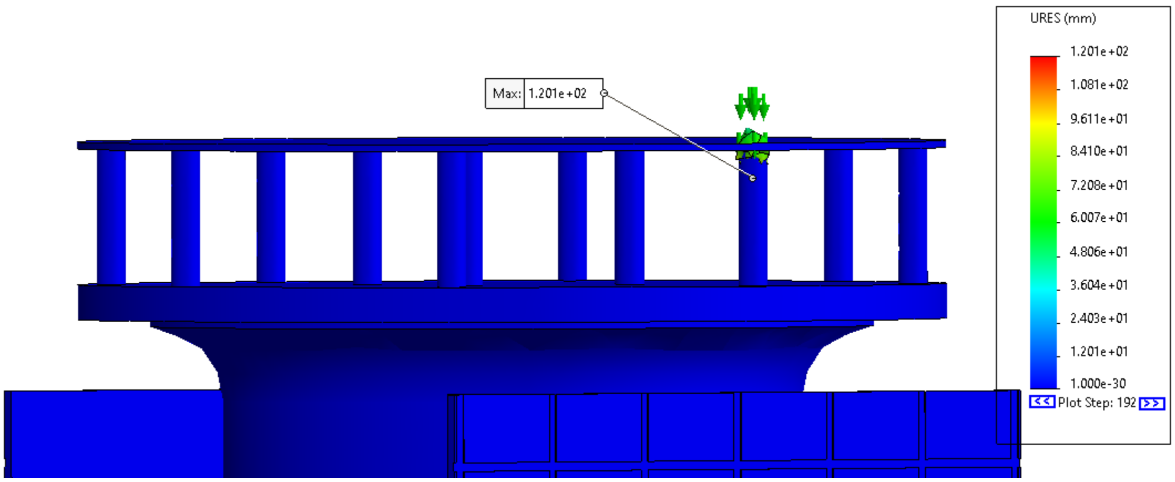

Figure 38: Impact Test 3 Results - Displacement

Figures 37 and 38 shows the resulting stress and displacement of Impact Test 3, respectively.

Appendix F.2: Dynamic Shock Load Simulation

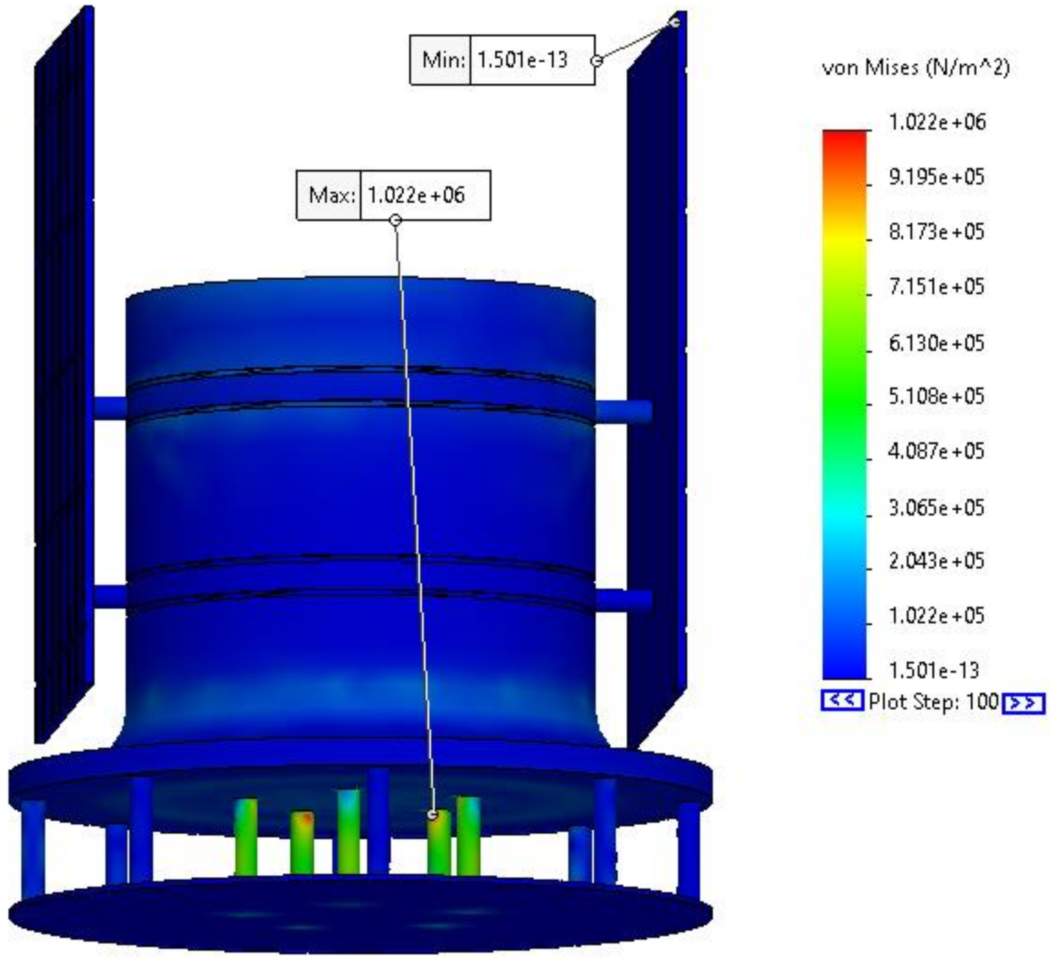

Figure 39: Dynamic 5G Shock Loading Results – Stress

Figure 39 shows the resulting stresses of the 5 Gs of acceleration experienced during stage 1 of launch. The maximum stress occurs at the base of the supporting rods connecting the bumper plate to the back wall. Using the yield strength of AA2024-T4, the factor of safety is calculated to be 318.

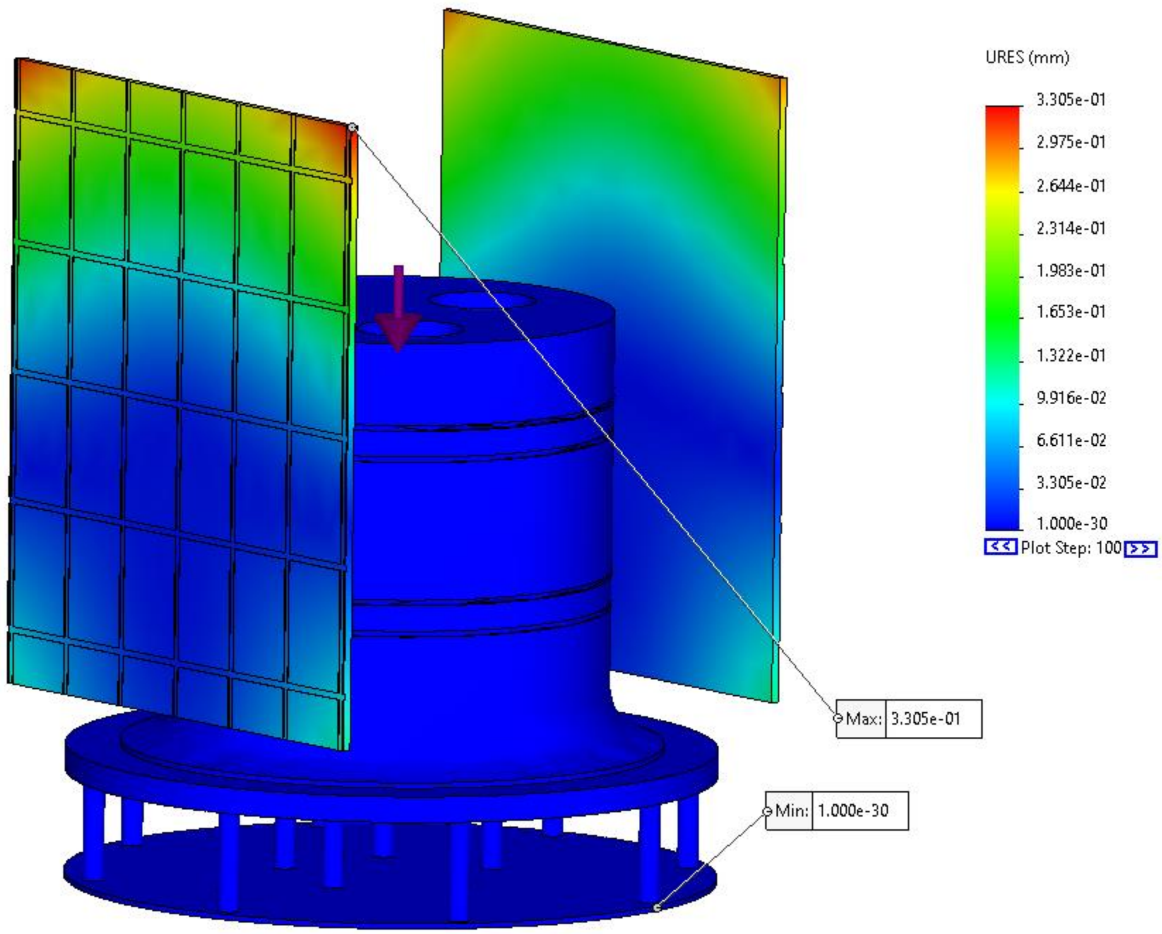

Figure 40: Dynamics 5G Shock Loading Results – Displacement

Figure 40 shows the resultant displacement experienced during stage 1 of launch. The maximum displacement occurs at the corners of the solar arrays, with a value of 0.33 mm. The fixtures for securing Scrappie to the Falcon Heavy payload fairing were assumed to be the bumper plate, main hull, and solar arrays. In reality, how Scrappie would be secured to the payload fairing would be determined by SpaceX.