REDUCTION OF SOLID FUEL HYDROXYL-TERMINATED POLYBUTADIENE COMBUSTION IN AIR USING A NON-PREMIXED COUNTERFLOW DIFFUSION MODEL

THE SPACE DEBRIS DILEMMA AND THE CONSEQUENCES OF LARGE CONSTELLATIONS

A Thesis Prospectus
In STS 4500
Presented to
The Faculty of the
School of Engineering and Applied Science
University of Virginia
In Partial Fulfillment of the Requirements for the Degree
Bachelor of Science in Aerospace Engineering

By
Del Irving

November 1, 2021

On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

ADVISORS

Catherine Baritaud, Department of Engineering and Society

Harsha Chelliah, Department of Mechanical and Aerospace Engineering

Periods in history are often defined by a certain window of time with a beginning and an end. For example, the Bronze Age lasted from approximately 3300 BCE to 1200 BCE and the Industrial Age spanned from 1760 CE to 1970 CE. Beginning in 1957 with the launch of Sputnik 1, the Space Age has seen some of the greatest achievements of mankind, from Apollo 11 and the first man on the moon in 1969 to the New Horizons mission traveling past the dwarf planet, Pluto, in 2015 (Johns Hopkins University Applied Physics Laboratory, 2021, para. 2). Constant development of new aerospace technologies hopes to bring spacecraft and humans further into the unknown of the solar system and beyond, but the window of the Space Age is already starting to close. Each new mission, successful or not, would see the addition of yet another metallic hunk introduced into orbit. In 2002, Crowther (2002) numbers around 9,000 cataloged (greater than 10cm in size) objects in orbit (p. 1242). By 2014, "NASA's Orbital Debris Program Office estimates that there are currently over 21,000 fragments larger than 10 centimeters in orbit" (Finkleman, 2014, para. 6). Today, over 27,000 pieces of orbital debris are currently being tracked by the Department of Defense's Space Surveillance Network, with much more lethal debris that is too small to be tracked but large enough to result in devastating collisions in Low Earth Orbit (LEO) (Garcia, 2021, para. 1).

The technical project focuses on creating a reduced model for the combustion of solid fuel butadiene with air, more specifically hydroxyl terminated polybutadiene (HTPB), in hypersonic engines. The current model takes several days to run but is extremely accurate so the goal of the research is to reduce the model to a point where calculations can be done rapidly but with the most accuracy possible for this level of reduction. This is done by modeling flamelets along the hybrid-propellant (gaseous oxidizer and solid fuel) boundary using a non-premixed counterflow diffusion model as outlined in Sarnacki et al. (2012, p. 1032). The technical work has strongest applications in the fields of hypersonic flight and rocket propulsion and has the potential to be the next big leap in rocketry to send spacecraft even further beyond what has been currently explored.

The motivation for the STS project on space debris is that if nothing is done about the inactive crafts aimlessly orbiting Earth, space travel will soon become obsolete and an end to the Space Age will come. The technical and STS research are moderately coupled based on this fact that if space junk is not dealt with rapidly, all aerospace research will soon become futile as the heavens are closed off by a layer of metal in low Earth orbit.

The technical and STS projects will be completed during the Fall 2021 and Spring 2022 semesters over the course of 30 weeks split up into two 15 week semesters. This work will be completed according to the Gantt chart in Figure 1.

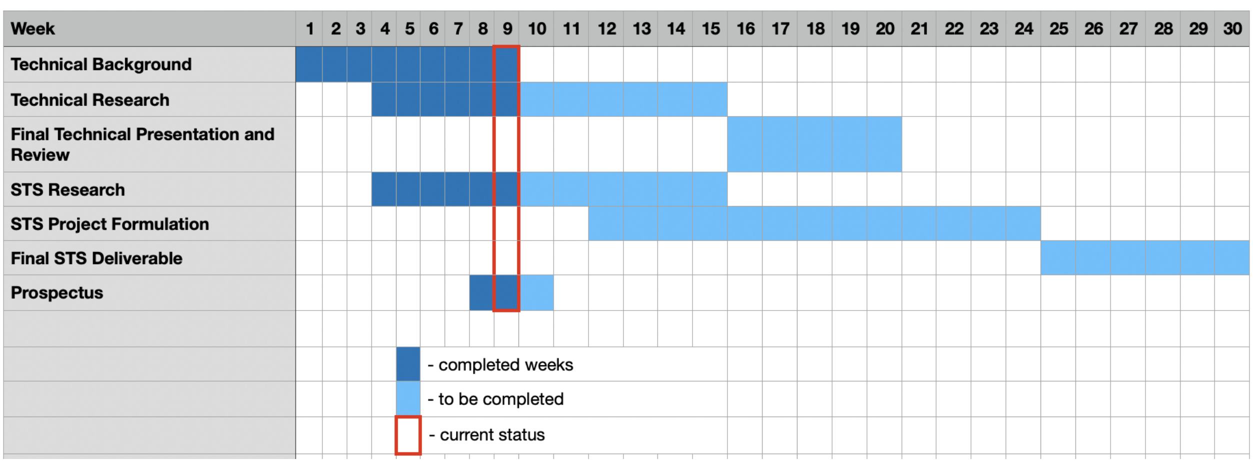

Figure 1: Gantt chart outlining technical and STS project future timeline along with current place within timeline. (Irving, 2021).

Most of the technical work for the project has already been completed and will be refined through the remainder of the Fall 2021 semester while an achievable deliverable for the STS project will be formulated through the end of the current semester and the beginning of the coming semester to be completed by the end of the Spring 2022 term.

REDUCTION OF SOLID FUEL HYDROXYL-TERMINATED POLYBUTADIENE COMBUSTION IN AIR USING A NON-PREMIXED COUNTERFLOW DIFFUSION MODEL

Hybrid propulsion offers a number of advantages over single-state engines and rockets such as increased chemical stability, greater safety of transportation and storage, higher performance, lower environmental impact, and cost efficiency on a number of levels (Calabro, 2011, p. 359). The Naval Research Laboratory (NRL) in Washington, D.C. favors hybrid propulsion for all of these reasons and has an outstanding model that is incredibly accurate, yet takes far too long to run when results need to be produced for quick analysis. When a final model is necessary, accuracy is a must, but during research when quick numbers are more important, a reduced hybrid propulsion model can save time and money on a large scale.

Working alongside Professor Harsha Chelliah, an undergraduate and graduate professor of mechanical and aerospace engineering at the University of Virginia, and the NRL, the objective of the technical project is to produce a reduced hybrid propulsion model of an HTPB-air reaction. This model will then be compared against existing models within the paper "CSP-based chemical kinetics mechanisms simplification strategy for nonpremixed combustion: An application to hybrid rocket propulsion" by Ciottoli et al. (2017) to ensure the accuracy of the reduction.

The approach taken will utilize a non-premixed counterflow diffusion model as depicted in Figure 2 on page 4 along the flame structure as the gaseous air combusts the surface of the solid HTPB.

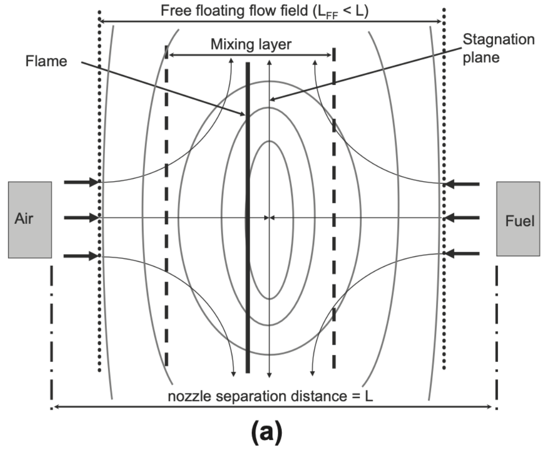

Figure 2: Non-premixed counterflow diffusion model with oxidizer flowing in from the left side and fuel flowing from the right. This specific model is for a free floating flow field which will be utilized in research. Flame structure sits closer to the oxidizer. Mixing layer represents a standard dimension. (Sarnacki, 2012, p. 1032).

Irregularities in the flame structure, called flamelets, make it so the plane along the flame is not perfectly linear. To solve this issue, each small section of the flame structure will utilize this non-premixed counterflow diffusion model to then be integrated across the entire structure in order to include all of the specific flamelets and give the overall model its accuracy without all of the additional computation time. This reduction is also accomplished by the reduction of the HTPB species data itself, using a file that only accounts for some of the compounds involved in the combustion.

In order to accomplish this research, the chemical kinetics software package, Cantera for Python, must be utilized. Within Cantera, reaction mechanism files in .cti format must be called which store all of the species and reaction data for a specific compound. These extremely detailed files are provided by the NRL for analysis. No additional hardware is required for this research since the reduction can be accomplished entirely through the use of code, though funding for this research is provided by Syntek Technologies, a contractor of the NRL.

End results of this technical project should demonstrate a code that is able to recreate the plots from Ciottoli et al. (2017) as shown in Figure 3.

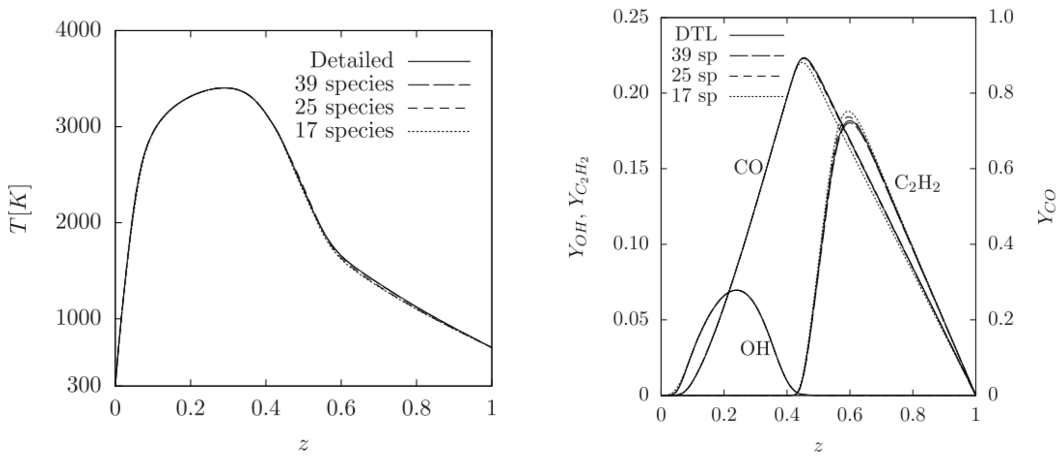

Figure 3: Temperature and mass fractions of OH, C_2H_2, and CO as a function of mixture fraction (defined as mixing layer in Figure 2) for three varying reductions of HTPB (17 species, 25 species, and 39 species) as well as a detailed model of the entire combustion for pressure at 3 bar. (Ciottoli, 2017, p. 86)

Once this has been accomplished, the code then becomes operational and can be implemented for a hybrid rocket propulsion system modeling across a wide range of fuel and oxidizer compounds. Current plots are close to those shown in Figure 3 but use rough estimates of species molecular weights and thus are not ready for further application. As described in Chelliah et al. (2003) the extinction condition of non-premixed counterflow flames are heavily influenced by smaller chemical species such as sodium bicarbonate ($NaHCO_3$) and thus a complete model must include a larger range of species (p.261). Once the results are finalized, a summary of the research and the accomplishments made as well as a comparison to the existing NRL model and the Ciottoli et al. (2017) models will be compiled into a technical report. This hybrid rocket propulsion is the perfect model for future space launch activities, in which “suborbital flights for tourism and scientific research are likely to represent the major part of this market” (DeLuca et al., 2013, p. 151).

THE SPACE DEBRIS DILEMMA AND THE CONSEQUENCES OF LARGE CONSTELLATIONS

Humans are driven by the unknown and the pursuit of knowledge, always searching for the ‘final frontier’. Since 1890 when the new world of America was completely settled, people began to look up to the stars for a new direction to travel. Today, talk of rocket launches and possible manned missions to Mars dominate news headlines and every other little kid wants to be an astronaut, and with overpopulation and climate change becoming increasing problems, some may believe space is the only hope for the future of humanity. However, there is one extreme issue that may put an end to space exploration once and for all, and nobody is willing to talk about it.

Tens of thousands of satellites continue to orbit Earth for years after they become inactive as visualized in Figure 4, deteriorating from communication necessity to metallic wrecking ball in a split second.

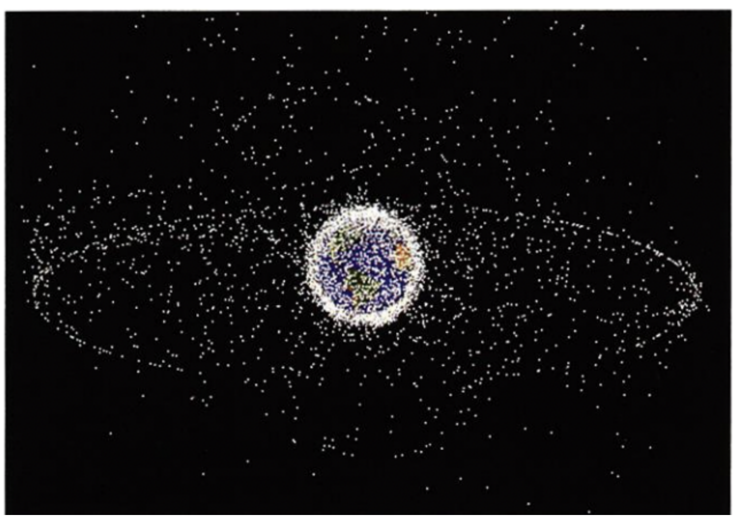

Figure 4: Visual representation of space debris. Close to Earth is a heavily concentrated zone of debris known as low Earth orbit (LEO). The ring further from Earth represents a geostationary orbit, common for communication satellites since the orbit remains above a fixed point on the surface. (Crowther, 2002, p.1241)

Although rare, large collisions between these crafts have taken place in the past and produce a myriad of fragments that continue around the planet in LEO like a shotgun spread waiting to impact the next object in their path. As debris becomes smaller and smaller, "there simply is no "one-size-fits-all solution" to the problem of space junk... removing large rocket bodies is a significantly different task than removing the equivalent mass of a lot more smaller objects, which are in a wide range of orbits" (David, 2021, para. 12). While proposed solutions are working to clear the larger bodies from orbit, there is still much to be done about debris in the 'lethal' zone, as depicted in Figure 5.

POPULATIONS OF ORBITAL DEBRIS

Population	Size	Number of objects	Percent number	Percent mass
Cataloged	>10 cm	>9000	<0.1%	>99%
Lethal	1@10 cm	>100,000	<1%	<1%
Risk	0.1@1 cm	>35,000,000	>99%	<0.1%

Figure 5: Populations of orbital debris by varying size and degree of concern with the most dangerous range of debris between 1 and 10 cm in size where the object cannot be detected but is still large enough to cause significant damage upon impact. (Crowther, 2002, p. 1242)

Between the exponential nature of these collisions and the constant addition of new satellites into orbit, it will not take long before the average spacecraft launch becomes impossible due to the layer of junk around Earth. There are a myriad of factors increasing this problem and the only proposed solution as of now is the ClearSpace-1 mission that aims to remove a mere 100 kilograms of space junk by 2025 (Biesbroek et al., 2021, p. 1). Of course this is a step in the right direction, but with companies like SpaceX and Blue Origin setting up large constellations of thousands of satellites, the net amount of debris in LEO is still increasing. SpaceX believes that they have found the solution to the space debris problem, and have even received approval from the "U.S. Federal Communications Commission ... to decrease the orbits of nearly 3,000 satellites in its Starlink constellation, reasoning that atmospheric drag would naturally sweep up dead satellites and debris in a reasonable amount of time" (O'Callaghan, 2021, para. 12). However, this assumption may be flawed since current NASA Debris Detection Software does not take into account the gradual atmospheric deterioration as a result of carbon dioxide emissions. As these emissions continue, the density of the atmosphere slowly decreases which reduces atmospheric drag at higher altitudes and thus the rate at which satellites are naturally incinerated. For this reason, climate change and the space junk problem go hand in hand and over time, debris will remain in orbit for longer and longer.

The objective of this STS project is first and foremost to bring attention to the issue space debris presents at a turning point where continuing to ignore the problem could present irreversible consequences in the near future. The good news is that there are currently solutions in motion to begin clearing debris such as ClearSpace-1 and many more creative ideas such as the plan to repurpose space junk, specifically aluminum, for construction of a lunar ground station that would save money and time by eliminating the need to transport materials back and forth between the surface of Earth and the moon (Koch, 2021, p. 2). This STS project could also be intended to formulate new ideas for space debris removal and potential repurposing, but between the difficulty required to design and construct such a technology within the next 20 weeks or so and the existing ideas going into effect within the next several years, writing a scholarly paper to raise awareness of the situation is the best course of action.

The entire space debris dilemma is best outlined by the Actor Network Theory (ANT) social model due to all of the commissions and aerospace companies that must work together to solve this problem, as depicted in Figure 6 on page 9.

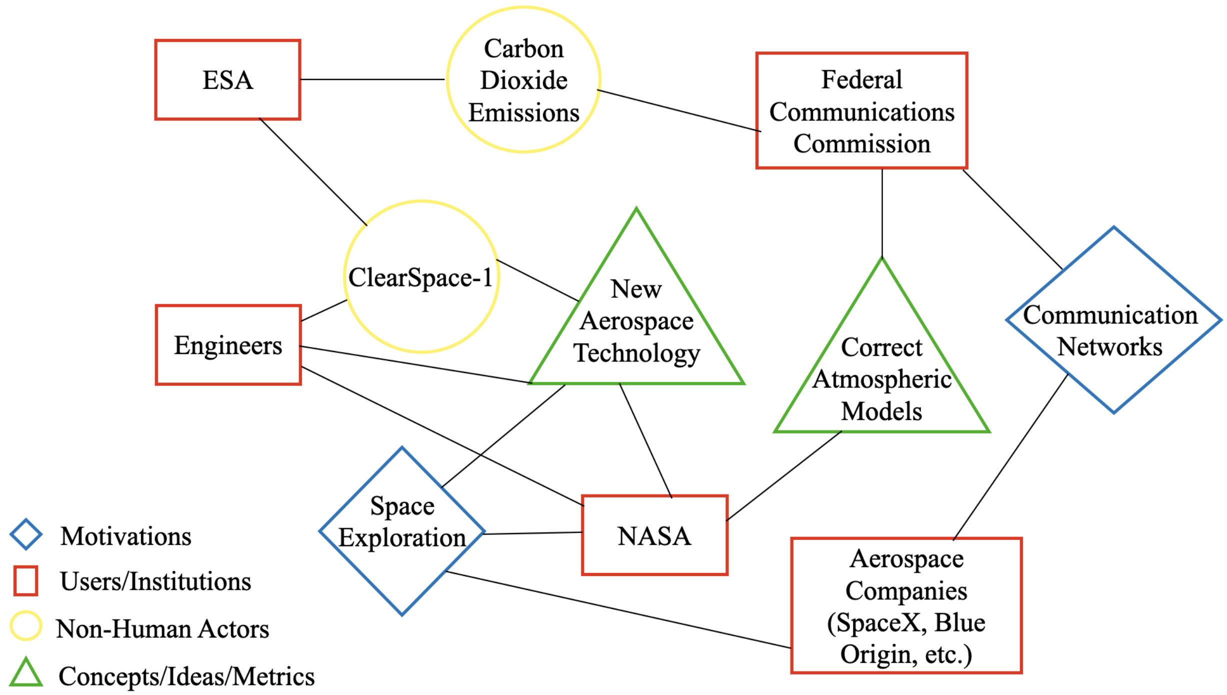

Figure 6: Actor network theory web relating motivations, users/institutions, non-human actors, and concepts/ideas/metrics for the space debris dilemma. (Irving, 2021)

In Figure 6, there is a clear overlapping of many interests, with the main countering positions being those in the blue diamonds: space exploration and the communications networks. With the addition of large constellations comprising thousands of satellites, these two motivations become mutually exclusive unless space debris can be cleared at a rate faster than new satellites are being launched. In the middle, new aerospace technology motivates engineers and NASA to support space exploration over communication networks and leads to the creation of spacecraft like ClearSpace-1 which is a significant step toward removing junk from LEO.

Ideally, the best outcome that could be expected is one where a rapid understanding of the direness of the space debris problem motivates companies to develop technologies intended to remove inactive satellites from LEO. This can be done by either forcing the bodies into the lower atmosphere to be incinerated or repurposing the material while at the same time continuing to develop and launch new satellites and rockets so that there would be no delay in space exploration. “ESA studies show that delay of remedial action until 2050 would be less effective than remedial regulation taking effect now” (Larsen, 2018, p. 495), further enforcing the need for action now before this problem begins spiraling beyond repair. It would also be necessary for the net rate of material in orbit to decrease to clear the way for not only new and improved technology but also for astronomical observation. If this is not possible the issue will have to continually be addressed until action is taken since this is not a problem that will change naturally, especially with increasing carbon dioxide emissions. The best course of action is to raise awareness about space junk before it is too late.

FUTURE AEROSPACE TECHNOLOGIES, SPACE EXPLORATION, AND A WORLD WITHOUT SPACE

As new and advanced aerospace technologies are developed, inactive crafts must be taken down simultaneously: out with the old in with the new. With space exploration on the brink of a large leap to putting humans on a planet other than Earth, hybrid propellant rockets may be the answer to faster travel within the solar system, and a reduced model would make calculations quicker. In space where everything occurs on such a massive scale, reducing transport time could make science fiction come to life even sooner than expected. As long as humans are willing to work together and undo the consequences of past mistakes, the future of space exploration will be very bright.

This research project will outline the reduction of a hybrid propulsion system with an HTPB-air combustion reaction to be used for further applications within the hybrid rocket field utilizing non-premixed counterflow diffusion models. The project will then attempt to bring attention to the issue of space debris by outlining the numerous potential consequences if no action is taken to the problem as well as highlighting current actions being taken to remove inactive satellites and smaller debris from LEO.

REFERENCES

Biesbroek, R., Aziz, S., Wolahan, A., Cipolla, S., Richard-Noca, M., & Piguet, L. (2021). The ClearSpace-1 mission: ESA and ClearSpace team up to remove debris. *ESA Space Debris Office*. https://conference.sdo.esoc.esa.int/proceedings/sdc8/paper/320/SDC8-paper320.pdf

Calabro, M. (2011). Overview on hybrid propulsion. *Progress in Propulsion Physics, 2*, 353-374. https://www.eucass-proceedings.eu/articles/eucass/pdf/2012/01/eucass2p353.pdf

Chelliah, H.K., Wanigarathne, P.C., Lentati, A.M., Krauss, R.H., & Fallon, G.S. (2003). Effect of sodium bicarbonate particle size on the extinction condition of nonpremixed counterflow flames. *Combustion and Flame, 134*, 261-272. https://www.sciencedirect.com/science/article/pii/S0010218003000920?casa_token=1L61MhdwO6kAAAAA:k7JqL0j1QAbxupqnheW0r66Kskd8W4W5MQ6Y0BvBJgLnKnemY-bT5XdjY-YiglQBJ65QL2fvfA

Ciottoli, P. P., Galassi, R. M., Lapenna, P. E., Leccese, G., Bianchi, D., Nasuti, F., Creta, F., & Valorani, M. (2017). CSP-based chemical kinetics mechanisms simplification strategy for non-premixed combustion: An application to hybrid rocket propulsion. *Combustion and Flame, 186*, 83-93. https://www.sciencedirect.com/science/article/pii/S0010218017302912?casa_token =TEGziKbXVS0AAAAA:I9virkEUVdy6CO22f8srN3RwP-FqAeW151F95v8QIGwOukcdyDE2PkLf3P-x_1_dl4MTp_TmKQ

Crowther, R. (2002). Space junk—Protecting space for future generations. *Science, 296*(5571), 1241-1242. https://www-jstor-org.proxy01.its.virginia.edu/stable/pdf/3076795.pdf?refreqid=excelsior%3Abaf5a35eb0347e5030399888ea8a7162

David, L. (2021). Space junk removal is not going smoothly. *Scientific American Space & Physics, 4*(2). https://www.scientificamerican.com/article/space-junk-removal-is-not-going-smoothly/#

DeLuca, L. T., Galfetti, L., Maggi, F., Colombo, G., Merotto, L., Boiocchi, M., Paravan, C., Reina, A. Tadini, P., & Fanton, L. (2013). Characterization of HTPB-based solid fuel formulations: Performance, mechanical properties, and pollution. *Acta Astronautica, 92*(2), 150-162. https://www.sciencedirect.com/science/article/abs/pii/S0094576512001841

Finkleman, D. (2014). The dilemma of space debris. *American Scientist, 102*(1), 26. https://www.americanscientist.org/article/the-dilemma-of-space-debris

Garcia, M. (Ed.). (2021, May 26). *Space debris and human spacecraft*. NASA. https://www.nasa.gov/mission_pages/station/news/orbital_debris.html

Irving, D. (2021). *Gantt Chart Outline.* [Figure 1]. *Prospectus* (Unpublished undergraduate thesis). School of Engineering and Applied Science, University of Virginia. Charlottesville, VA.

Irving, D. (2021). *Space Debris Actor Network Theory Web.* [Figure 6]. *Prospectus* (Unpublished undergraduate thesis). School of Engineering and Applied Science, University of Virginia. Charlottesville, VA.

Johns Hopkins University Applied Physics Laboratory. (2021). *Using Charon-light researchers capture Pluto's dark side.* http://pluto.jhuapl.edu/News-Center/News-Article.php

Koch, F. (2021). The value of space debris. *ESA Space Debris Office*. https://conference.sdo.esoc.esa.int/proceedings/sdc8/paper/3/SDC8-paper3.pdf

Larsen, P. B. (2018). Solving the space debris crisis. *Journal of Air Law and Commerce, 83*(3), 475-519. https://scholar.smu.edu/cgi/viewcontent.cgi?article=4092&context=jalc

O'Callaghan, J. (2021, May 25). When space junk meets climate change. *The New York Times*. D4. https://link.gale.com/apps/doc/A662816475/UHIC?u=viva_uva&sid=bookmark-UHIC&xid=c0d7687f

Sarnacki, B. G., Esposito, G., Krauss, R. H., & Chelliah, H. K. (2012). Extinction limits and associated uncertainties of nonpremixed counterflow flames of methane, ethylene, propylene and n-butane in air. *Combustion and Flame, 159*(3), 1026-1043. https://www.sciencedirect.com/science/article/pii/S0010218011002823?casa_token=LUHWXtF_UPkAAAAA:5M_0yZunPPdAkHjDJaF62C4biW2U-wz9ZcH6gDQWGgtjqtL0V_Wfsh81CDgPMbTPNg52YdjaIg