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Energy Analysis For In-Situ Utilisation Of Space Debris

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1.1 Acronyms

SDO - Space Debris Objects

ESA - European Space Agency

DISCOS - Database and Information System Characterising Objects in Space

LEO - Low Earth Orbit

IGC - Inert Gas Condensation

AAC - Active Aluminium Content

TAPR - Transferred Arc Plasma Reactor

RFITPR - Radio Frequency Induction Thermal Plasma Reactor

DCAPR - Direct Current Arc Plasma Reactor

ID - Inner Diameter

OD - Outside Diameter

HRTEM - High Resolution Transmission Electron Microscopy

SP - Solid Propellant

ADR- Active Debris Removal

1.2 Nomenclature

F - Thrust

$\dot{m}$ - mass flow rate

p_e - exit pressure

p_a - atmospheric pressure

A_e - exit area

A_t - throat section area

γ - specific heat ratio

ϕ - fuel equivalence ratio

R_p - propellant gas constant

T_e - exit temperature

M - Mach number

r - burn rate

a - burn rate coefficient

n - propellant burn rate exponent

I_{sp} - specific impulse

g - gravitational constant

2 Introduction

Since the launch of the first object to space in 1957, the advances in the space industry made further missions more feasible both economically and technically. This however, have contributed to the increased amount of waste dumped on the orbits [1]. This waste, also known as the Space Debris Objects (SDO), describes any human-made objects that are no longer of use due to their malfunctioning, deorbiting, explosions or collisions and remain in orbit, rotating around the Earth [2].

In the past few decades the amount of SDOs increased exponentially posing many risks to the future space projects, as the objects as small as 0,2mm are of a great threat [3]. The problem could escalate even further according to the Kessler Syndrome, which states that the more junk we have in space, the higher the probability of collisions and creation of new, smaller debris. More smaller particles flowing around the Earth pose a direct danger to the International Space Station and its crew. The repercussions however, reach much further than that as the debris would impact the stable space environment of the orbiting satellites. That, on the other hand, translates into a disruption of most space-based applications on which our everyday life relies, such as weather forecasting, telecommunications, and the GPS [2] [4].
Figure 1 is a visual representation of the Kessler Syndrome.

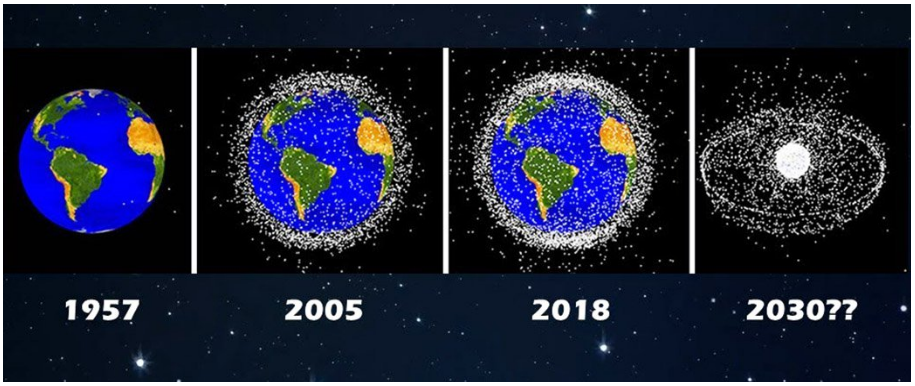


Figure 1: Volume of Space Debris over the years [5]

According to the analysis of the European Space Agency, the majority of launches from the 1990s are due to commercial reasons. While it is very hard to limit the civil and defense payload launches simply because of the importance they have in our everyday life, focusing the efforts on limiting the commercial launches is a good place to start. This however can be a very hard task due to the highly advertised nature of commercial launches. For instance, the current Tesla - Besos space race and the idea of making profit by bringing humans to space is a strong case for increased launches in the public eye.

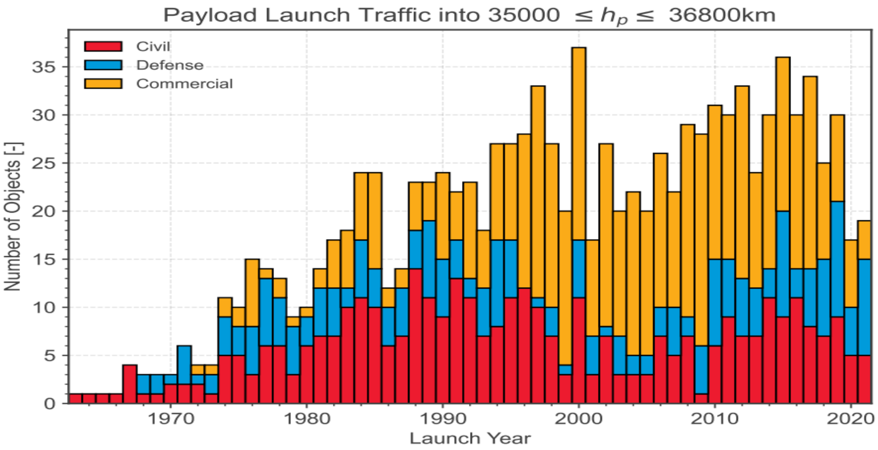


Figure 2: Space traffic by sector [6]

Although the zero waste and recycling topics have become an integral part of our everyday life, the issue is still new for the space industry and equivalent solutions to those already implemented on Earth must be found. Some removal techniques have been around since mid 2010s and include a net, which purpose is to deorbit the desired waste and let it burn upon atmospheric reentry [7]. While this type of SDOs removal certainly helps declutter the orbit, it is equivalent to incinerating our waste on Earth without taking advantage of their benefits if reused.

Recycling, nowadays a crucial part of our everyday life has as many benefits in the outer space as it does on Earth. Once the desired debris is identified, captured, and collected it can serve as a source of many valuable materials that can be reworked to give life to new objects. Such process would decrease the load that needs to be brought to space from Earth. There are various scenarios of how such recycling process would take place. One possibility would be to recycle the debris directly on the International Space Station or, in a more ambitious scenario, build recycling stations on the Moon that could also serve the future Moonians. The space available on the ISS is, however, a serious limitation for incorporating the recycling station into the ISS. Moreover, the risk coming from the recycling operations themselves could impact the operational mode if something does not go as planned and could jeopardize the station's operation as well as the safety of the crew. Moon's environment, on the other hand, is thought to be an excellent place to set up a recycling unit.First and foremost, the vast area available allows the expansion of the plant if needed. Secondly, the unit can be easily incorporated into a complex infrastructure to adapt to the future settlements. Last but not least, Moon's low gravity (as compared to Earth) is thought to be of a great benefit, as it eases the precise heat monitoring. Furthermore, low gravity environment is excellent for high purity metal production as it supports precise control of movement and orientation of particles, making gravitational segregation almost negligible

[8]. Moreover, Sun can deliver the required energy to power the entire operation. Space debris recycling however, requires a lot of work input in terms of preparation of a detailed list of the SDOs, their size, the materials they are made of, as well as the planning and logistics of the entire process [9].

The scope of this work is to first identify the most attractive material, in terms of availability, recycling and manufacturing techniques, as well as the final use. Once this part is completed, the recycling cycle will be designed followed by the process' mass balance. The cycle will include the transportation of the SDOs to the unit on the Moon, separation of the desired material from the scraps and its preparation to further manufacturing. Subsequently, the process of transforming the desired material into a specif output is described. Finally, the end use is illustrated.

3 What to recycle

In order to build a strong case for the implementation of recycling units on the International Space Station (ISS) or the Moon, it is crucial to first identify and quantify the available resources in these environments. However, this task presents a significant challenge as the currently collected data do not provide the desired level of accuracy. Nevertheless, the establishment of a detailed data set is essential for effective recycling practices in the future.

The European Space Agency (ESA) has already made commendable efforts in this regard by creating the Database and Information System Characterising Objects in Space, also known as DISCOSweb. This platform serves as a comprehensive reference for crucial information related to space missions and objects. It provides data on launch information, object registration details, launch vehicle descriptions, spacecraft information such as size, mass, shape, mission objectives, and owner, as well as orbital data histories for over 40,000 trackable, unclassified objects [10].

In the future, DISCOSweb has the potential to expand its capabilities and incorporate the missing object information. In a more ambitious scenario, it could even incorporate real-time data from RADAR/LASER observations [11]. This would significantly enhance the accuracy and comprehensiveness of the database, thus enabling better decision-making regarding recycling initiatives.

Updating the DISCOSweb database would be relatively straightforward as all future space servicing missions would be required to provide detailed information. Therefore, no additional costs would be incurred for regularly updating this valuable resource [10]. By allowing end users to browse the database and access desired information, including launch information, launch vehicle description, spacecraft information, and detailed compositions and technical information about objects, stakeholders can make informed decisions regarding recycling efforts in space [11].

Ultimately, the expansion and continuous update of the DISCOSweb database would provide a solid foundation for advancing recycling practices on the ISS, the Moon, and other space environments. It would enable scientists, engineers, and space agencies to gather comprehensive data and make informed choices regarding resource utilization, waste management, and sustainability in space exploration[12].

3.1 Space Objects Analysis

The increasing traffic on the orbits, both in terms of the number of objects and their mass, has raised concerns about space debris and the possibility of the Kessler Syndrome, where the collision of space objects creates a cascade of debris that poses a significant threat to operational satellites. One potential solution to mitigate this problem is recycling the materials present in space. It is evident that there is no shortage of materials with recycling potential on the orbits. However, the question that arises is whether to focus on recycling all of these materials or to prioritize a few most promising ones.

Data provided by the European Space Agency (ESA) and the Database and Information System for Dismantling and Recycling of Space Objects (DISCOS) reveals that the majority of space debris is concentrated in the Low Earth Orbit (LEO). This information indicates that efforts to recycle space debris should initially focus on LEO.

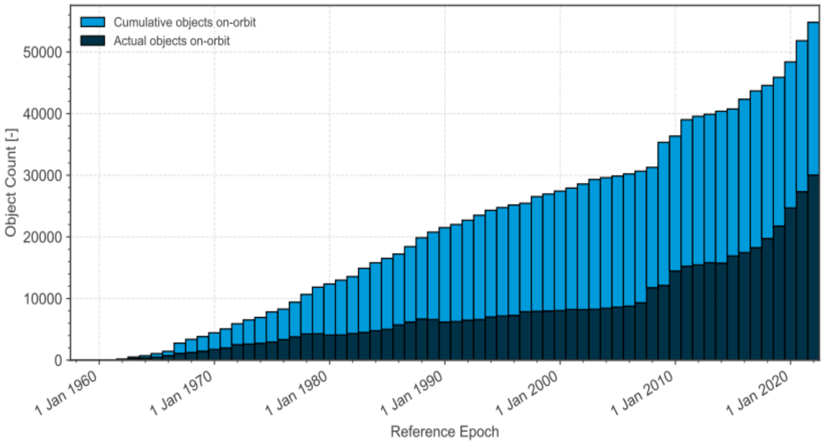


Figure 3: Objects count in all orbits [6]

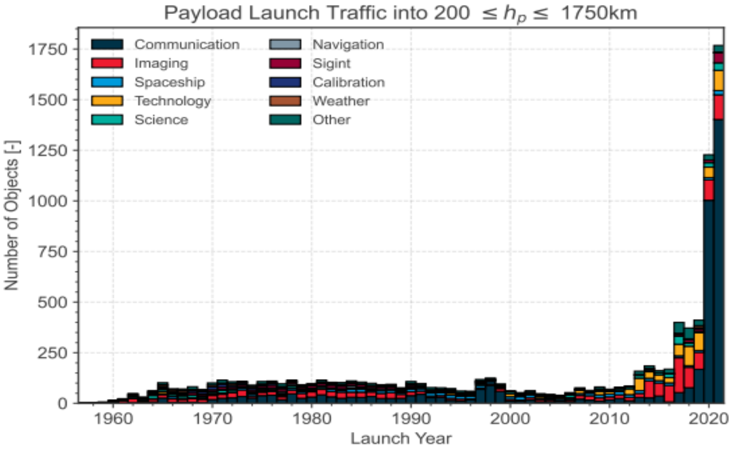


Figure 4: Launch traffic near LEO by mission type [6]

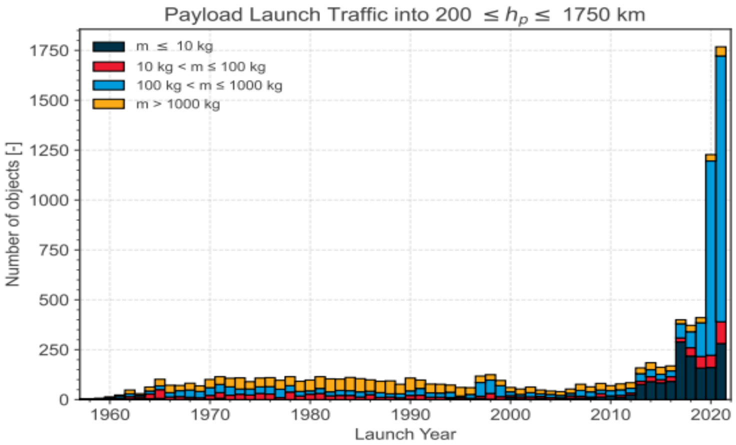


Figure 5: Launch traffic near LEO by mass [6]

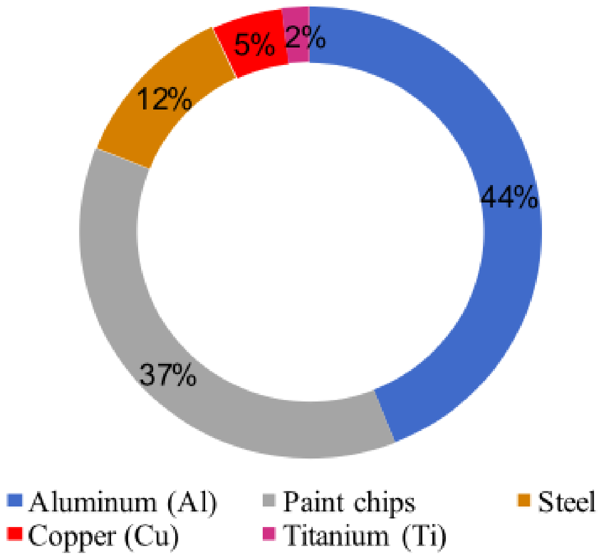


Figure 6: Percentage of material frequently bowing on ISS [13]

Additionally, an analysis of objects colliding with the International Space Station (ISS) has provided valuable insights into the composition of materials in LEO. Figure 6 illustrates that aluminum is the most abundant element present in LEO. This alignment with the common trend of using aluminum in the space industry, such as in space shuttles and equipment, highlights its significance [14]. Aluminum is considered an ideal candidate for space recycling due to its abundance in LEO, its infinite recyclability, and the relatively easy and cost-effective recycling processes involved. By focusing on recycling aluminum in space, it is possible to reduce the amount of new space debris generated and create a sustainable approach to space exploration and satellite operations [15].

In conclusion, the concentration of space debris in LEO and the abundance of aluminum in this orbit present opportunities for the space recycling industry. Prioritizing the recycling of aluminum can effectively mitigate the growth of space debris and contribute to the sustainable management of space resources. Extended efforts and research are needed to develop efficient recycling methods and strategies that ensure the long-term viability of space operations.

3.2 Aluminium Insights

Aluminium is widely used across many industries due to its ductility, conductivity, and an outstanding corrosion resistance. It is also very well-known for its non-toxicity [16]. Taking into consideration the aforementioned advantages of aluminum combined with its recyclability potential, reworking it for propulsion purposes can be attractive for space industry as it is an excellent way of reducing the weight of the launched rockets and therefore cut the fuel consumption at the beginning of the mission. Due to its high energy density and combustion temperature Al powder is being used in the propellant production industry for decades, which consequently provides a vast amount of related research and certainly a great fundamentals to further improve the process [17]. The current interest, among others, revolves around different particle diameters and their influence on the burning rate as well as the ignition time and temperature [18].

Nano-sized aluminum propellant powder is becoming more and more appreciated as compared to its normal and micro sized sisters. Aluminum particle size varies between 50 and 300nm and is highly desirable mostly thanks to the increased burning rates and shorter ignition delays it can provide. If executed poorly however, nAl particles could lead to poor mechanical properties as well as thick Al_2O_3 layers [19]. The latter could cause a significant impulse reduction, which might be improved with coatings. Unfortunately, very little research has been done so far to address the topic [20]. Until now most aluminum-based propellant powders are micrometric which provide optimal increase of density and modification of the burning rate. Although, despite wide popularity and use of micro Al it is not without a flaw. It posed many problems during metal combustion as it translates into an oxide layer creation which in turns hinders ignition [20]. However, as the technical capabilities are increasing over the years, it is becoming more and more feasible to create nano aluminum powders. Even though each magnitude order of particle diameter has its pros and cons, the overall use of aluminum in the solid propellant industry is so common and efficient that translating this knowledge to space fuel fabrication might be worth the effort

4 Nano Aluminium Powder Production

Typical solid rocket fuel is made of fuel, catalyst oxidizer and a polymer binder. The first three components correspond to aluminum powder, iron oxide and ammonium perchloride, respectively [21]. In the Moon environment, however, procurement of all the ingredients could be quite challenging and a simplified alternative had to be though of. There had been many experimental and theoretical studies, which mostly focused on finding easily accessible materials as fuel, something to burn, and an oxidizer, something to initiate the reaction [22]. As a result, a reaction of aluminum with water was proposed. It is an excellent solution for lunar environment, as oxygen can be produced from regolith and aluminum from space debris transported from LEO. Such propellant needs to be stored in a solid form, as ice, hence its name ALICE [23]. The combustion is described by the following reaction:

$$2Al + 3H_2O \rightarrow Al_2O_3 + 3H_2 \tag{1}$$

In order to achieve this final step, first both the Al and H2O must be prepared. As discussed in the previous sections, nano-Al offers a lot more in terms of burning rates and shorter ignition delays than their "bigger" sisters. Therefore, it is used in ALICE production. There are various methods to reduce the size of SDOs among which mechanical ball milling, exploding wire or gas evaporation [24]. Exploding wire is a very popular method among researchers nowadays, however very little information about the efficiency and energy consumption is available as well as its scalability. For this reason, the method taken into consideration in this paper is the Inert Gas Condensation, which is being used for over two decades to produce nano particles [25]

4.1 Debris Transportation to the Moon

Prior to planning any type of lunar-based recycling station, an efficient delivery of space debris from the orbits must be designed. Most SDOs are in the Low Earth Orbit, hence the initial transportation system should start here [26]. Researchers are constantly working on new ways to tackle the problem of piling debris in the orbits. For instance, Airbus' RemoveDEBRIS system employs two capture methodologies, namely net deployment and a harpoon-like device. The net-based approach mimics the principles of fishing, ensnaring debris by deploying a net that entangles objects within its reach. The harpoon method involves firing a specially designed harpoon at debris to secure it. Once captured, the debris is expected to undergo controlled re-entry and burn up upon re-entering Earth's atmosphere, effectively reducing space debris concentrations [27].

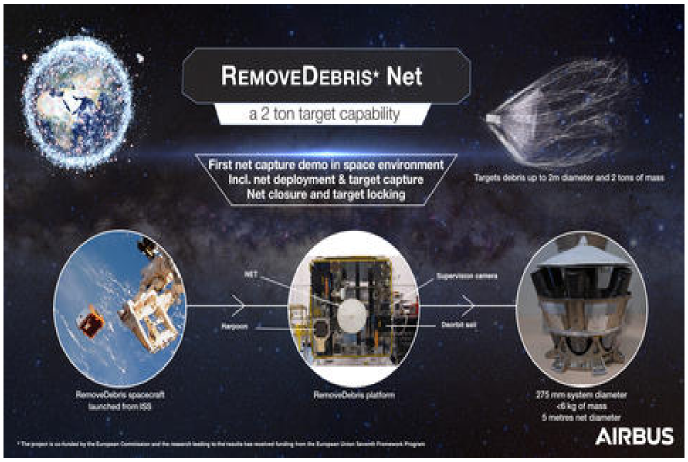


Figure 7: Airbus Net [27]

Figure 8: Airbus Harpoon [27]

The European Space Agency has also been developing an active debris removal system to address the growing space debris problem. Their approach involves deploying a chaser satellite equipped with robotic arms to capture and remove debris. The captured debris is then directed towards re-entry or is transported to a higher graveyard orbit [28].

When comparing the pros and cons of Airbus' RemoveDEBRIS system, the versatility of capture methods and the reduction of uncontrolled fragmentation stand out as significant advantages. However, the system lacks options for debris recycling and still carries a risk of smaller fragments surviving re-entry. On the other hand, the harpoon method excels in efficient capture and minimizing fragmentation risk. However, it may struggle with capturing smaller debris and also lacks transport flexibility. Moving on to ESA's Active Debris Removal system, the precise capture capabilities and multiple disposal options are major strengths. However, the techni-

Figure 9: ESA's Active DEbris Removal [28]

cal complexity and high costs associated with developing and implementing the system pose significant challenges. Overall, each method offers unique benefits and drawbacks, highlighting the need for further research and development to address their limitations and enhance their effectiveness in tackling space debris. At the moment, however, the ESA's ADR is the best candidate for the debris transportation to the Moon.

4.2 Scraps Preparation

After having collected and transported the debris to the Moon it need to undergo series of operation before it can be used as a propellant. First and foremost, any contaminants such as dirt, oil or pain need to be removed. It is a necessary process due to the alloys, coatings, and contaminants negatively affecting the purity of the resulting aluminium blocks [29]. If more elements are included in the debris, magnets can be used to separate ferrous and non-ferrous materials together with X-Ray technology during a inductive sorting to sort different types of metals [30] [31]. After that, high-purity aluminum is shredded into small parts to increase their surface area. Lastly, the pieces are scrubbed clean using mechanical and chemical processes to provide a high quality powder for the Inert Gas Condensation process [32]. Aluminum recycling process, despite being relatively simple and straightforward, is highly efficient. In fact, *"75 percent of the new aluminum produced since the 1880s is still in use in one form or another"* [33] and the material loss during recycling processes can be assumed negligible [34]. Thanks to this process, not only aluminium can be recovered, which is the main interest of this study, but also other materials that can be reused on the Moon.

4.3 Inert Gas Condensation

The inert gas condensation method is one of the most known and used technique for the synthesis of nanostructured materials. This method has been used to produce a wide range of nanomaterials, including metals, metal oxides, and other materials. One such material that can be produced using the IGC method is nano aluminum powder. The conceptual design of the IGC process can be seen in figure 10.

It involves vaporizing the material of interest and then rapidly condensing it by quenching the vapor with an inert gas, typically helium, argon or xenon. Each gas is found to enhance the production of smaller particles, respectively. for the optimal conditions argon is used as it guarantees the particle size over 100nm [35]. In the case of producing nano aluminum powder, high purity aluminum is heated in a vacuum chamber to a temperature above its melting point. The resulting vapor is then rapidly cooled by the inert gas, leading to the formation of nano-sized aluminum particles. The size of the resulting particles can be controlled by adjusting the temperature and pressure of the process [36]. To achieve the best efficiency in the IGC method, several factors should be considered. Firstly, the starting material, in this case, high purity aluminum, must be carefully prepared to ensure that it meets the requirements for the process. The temperature and pressure of the process should be carefully controlled to produce particles with the desired size and morphology. Additionally, the gas flow rate and the nozzle design should also be optimized to achieve the best yield and particle size distribution [37]. The synthesis efficiency is assumed to be 90% [38].

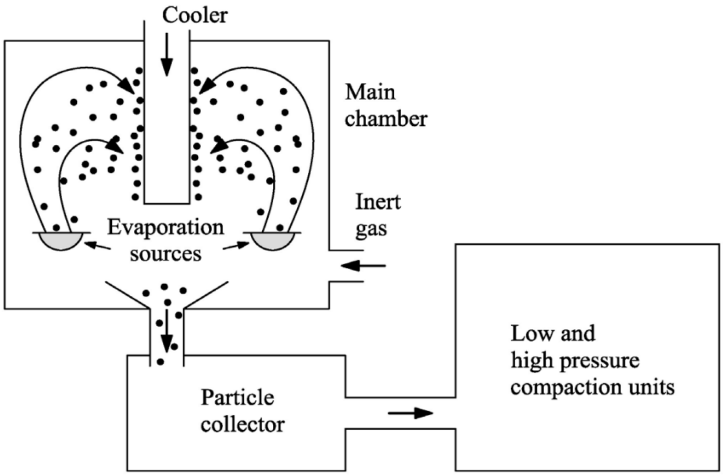


Figure 10: Inert Gas Condensation Scheme [36]

There are different techniques available for material evaporation, such as thermal or laser evap-

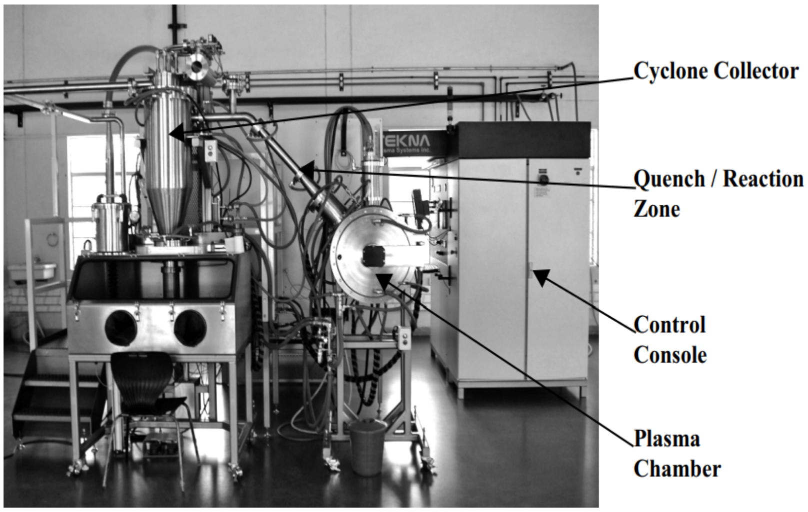
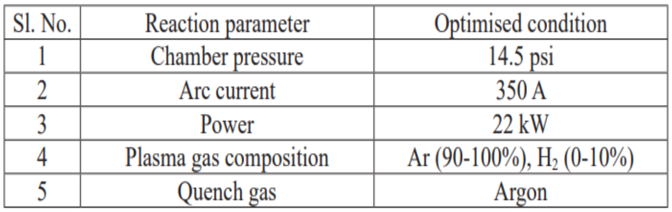


Figure 11: TAPR equipment [39]

oration, sputtering, electrical arc discharge, and plasma heating [40]. In this paper the thermal plasma method is used and from now on will be referred to as Transferred Arc Plasma Reactor (TAPR) method. Arti PANT *et al.* [39] analyzed the process thoroughly and were able to optimize the process obtaining particles in a size range 50-250nm with a production rate >50g/h. Process parameters are reported in table 12. The powder produced is very competitive in terms of active and total aluminium contents as compered to other samples produced using methods such as electrical wire explosion (ALEX), DC arc plasma reactor (DCAPR), RF induction thermal plasma reactor (RFITPR). Furthermore, a comparison is made with the commonly used micron sized powder as well. The results are reported in table 13 and it can be seen that the TAPR powder presents itself well in terms of Active aluminium content and total aluminium content, which amount to 86.9% and 92%,respectively.



Sl. No.	Reaction parameter	Optimised condition
1	Chamber pressure	14.5 psi
2	Arc current	350 A
3	Power	22 kW
4	Plasma gas composition	Ar (90-100%), H_2 (0-10%)
5	Quench gas	Argon

Figure 12: Optimized process conditions [39]

NAP Sample	AAC [%]	STDEV σ	TAC [%]	STDEV σ
EEW, (ALEX, Russia)	85.5	0.66	96.3	0.4
DCAPR, (UOP)	70.0	0.56	85.0	0.7
TAPR, (C-MET)	86.9	0.32	92.0	0.34
RFIPR, (ARCI)	75.6	0.49	85.6	0.26
Micron-Aluminium powder, (HEMRL)	98.7	0.33	100.8	0.71

Figure 13: Active and total aluminium contents of different samples [39]

4.4 Powder Characterisation

The first visible characteristic of the powder is it's colour - it gets darker with the particles size decreasing. Hence, it's a good first inspection method, as the desired powder should be of a blacker shade.

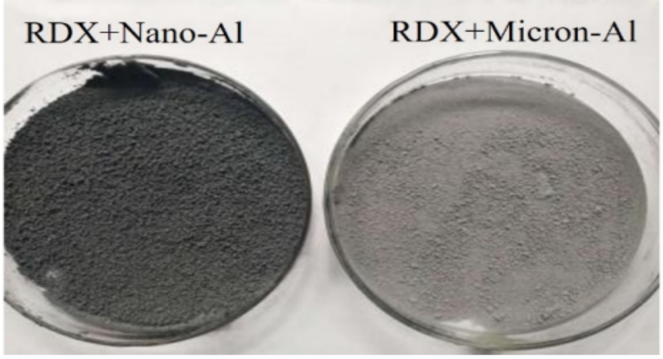


Figure 14: nano vs micro alumiunum powder colour [41]

Furthermore, the particle's size influences the surface area and all properties related, such as reactivity. *Jun Dong et al* describe it as followed: *"The high surface area of nanopowders is illustrated by considering a 100 g mass of aluminum metal, a mass roughly equivalent to the size of a golf ball. The surface area of this 100 g piece of aluminum would be 5.4 × 10–3 m2, approximately the size of a typical 3-inch Post-It® note. When this 100 g mass of aluminum is converted into 40-nm powder the surface area is increased to 5,500 m2, or roughly the size of a soccer field. The single golf ball mass of aluminum would be converted into 1018 40-nm n-Al particles, or roughly one particle for ever square centimeter of land on the planet Earth."* [36]. That is to say that the smaller the particle's size the higher its reactivity, for instance a micron aluminium powder will require a high energy input, while a nano powder will burn upon immediate exposure to a flame [36]. Upon further inspections it is detected that produced powder has a thin oxygen layer, so small however that it does not hinder its performance as a fuel and can be considered as "dead weight" [39]. After the powder is prepared its density can be then measured. In this study however, this value will be assumed constant and equal to 2700 g/cm3 [42].

Thanks to the High-Resolution Transmission Electron Microscopy (HRTEM), the nano powder produced can be seen in a great detail. It can be further compared with other powders available, as seen in figure 15.

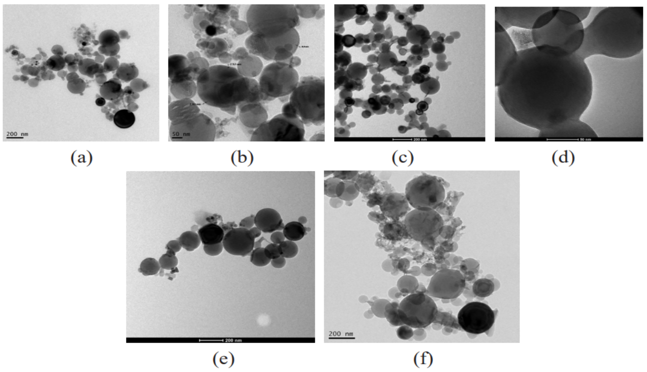
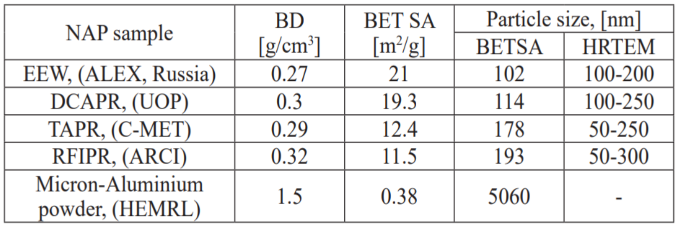


Figure 15: (a) and (b) TAPR, (c) and (d) ALEX, (e) DCAPR, (f) RFIPR [39]

Moreover, table 16 shows a comparison between particle size produced and the average bulk density (BD) and surface area (BET).



NAP sample	BD [g/cm^3]	BET SA [m^2/g]	Particle size, [nm]	
			BETSA	HRTEM
EEW, (ALEX, Russia)	0.27	21	102	100-200
DCAPR, (UOP)	0.3	19.3	114	100-250
TAPR, (C-MET)	0.29	12.4	178	50-250
RFIPR, (ARCI)	0.32	11.5	193	50-300
Micron-Aluminium powder, (HEMRL)	1.5	0.38	5060	-

Figure 16: particle size, bulk density and surface area of different powders [39]

In terms of particle size distribution, the first two samples are of similar range and the same comes for TAPR as compared to RFIPR. More detailed analysis of the ALEX powder showed that particles are connected between themselves through the oxide layer which is a direct result of particles clustering during oxidation, a phenomenon to be avoided as it leads to inhomogeneities within the powder and hindering of its efficiency. Furthermore, wider particle size range can be the reason for higher AAC in the TAPR samples [43]. Looking at the correlation between particle size and active aluminum content in figure 17 it can be seen that beyod the diameter of 200nm the AAC stagnates at about 90% while the oxide layer thickness tends to increase. Hence, it is crucial to have a prevailing number of particles with diameter below, or up to, 200nm and in the best case scenario keep it around 100nm as the powder proves to be relatively stable with high active aluminum content [44].

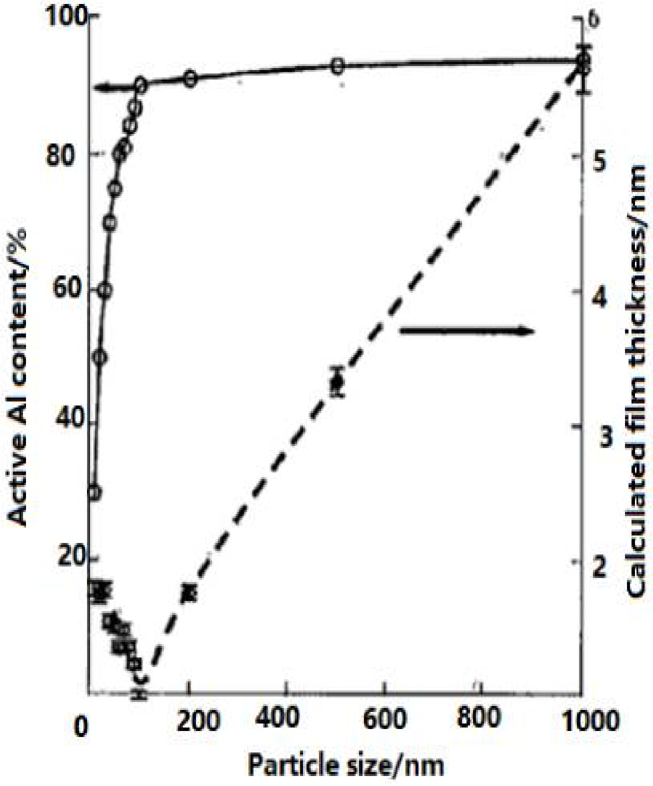


Figure 17: particle size vs AAC and oxide layer [44]

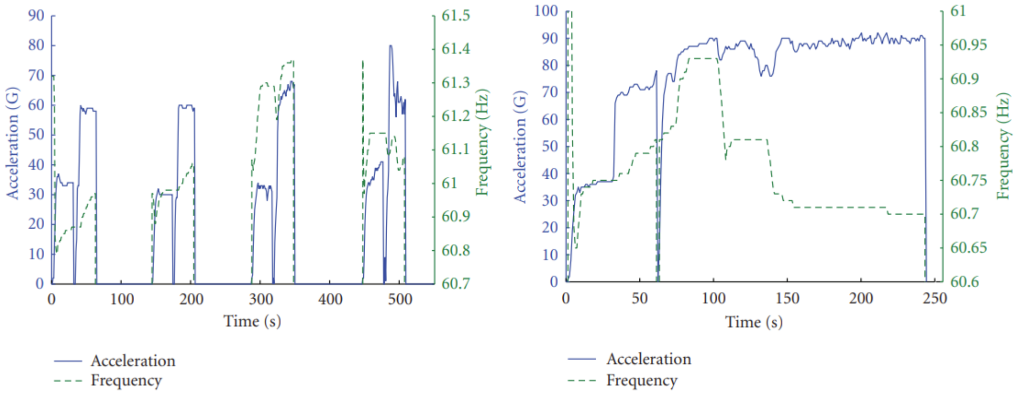
4.5 Powder Mixing and Casting

Initially, the powder mixing was done manually or using a Ross DPM-1Q dual planetary mixer. However, both techniques were abandoned due to inconsistencies in the final mix and packing densities. It was ultimately determined that perfectly cleaning the mixing equipment is of paramount importance to avoid contamination.

To address this issue, the ALICE propellant was mixed using a Resodyn LabRAM resonating mixer, which operates at the resonant frequency of the system being mixed. This mixer allows the user to specify the intensity of the mixing process. The density and viscosity of the mixture change as it is mixed, resulting in variations in the resonant frequency and the energy input. Monitoring these changes in acceleration and frequency is crucial in assessing the completeness of the mixing process.

During a typical mix, the frequency of the mixer oscillates, while the acceleration generally continues to rise. These fluctuations occur due to the changing properties of the mixture throughout the mixing process. The ALICE propellant formulation consists of deionized water and nanometric aluminum powder. As the mixing progresses, the mixture initially forms clumps until it eventually reaches a state of uniformity and becomes a paste-like substance.

To ensure the propellant is fully mixed, it is essential to achieve a state of uniformity in its properties. This indicates that the mixture is free from any contamination and ready for use [45]. Once this state is reached, both the acceleration and frequency level off for a period of time, indicating that the mixing process is complete. The importance of perfectly cleaning the mixing equipment cannot be overstated as any contamination could compromise the quality and performance of the final propellant product [46]. The figure below shows the development of the mixing process.



(a) (b)

Figure 18: (a) the fluctuation in speed and frequency over successive mixing cycles; (b) the speed and frequency during a single mixing cycle that maintains a relative consistency in intensity [46]

(a) (b) (c)

Figure 19: Mixing consistencies after: (a) first cycle, (b) second cycle, (c) final cycle. [46]

The next step after mixing the powder is casting the propellant into a solid propellant grain. It involves a precise process to ensure optimal performance. The first step is to prepare the casting hardware, which is designed using a CAD program to model the desired shape. The hardware is carefully designed with chamfers and tapered features to facilitate the extraction of mandrels and other components later on [45].

The propellant is then packed into the casting hardware, taking care to remove any air bubbles by using a rod to tamp it down. It is crucial to achieve a homogeneous and void-free propellant to maintain consistent thrust profiles and performance [47].

After allowing the propellant to cure for an appropriate timeframe, the casting hardware is carefully removed. This step may require some effort, especially for components like mandrels or seals, to avoid damaging the motor.

Once the casting hardware is removed, a thorough inspection is conducted to identify any voids or imperfections in the propellant. If voids are detected, they should be addressed to ensure optimal performance. This may involve modifying the motor's geometry or design, or in some cases, removing specific sections of the propellant grain that contain most of the voids [47].

Simulation tools can be used to assess the motor's performance and make informed adjustments to optimize its design. This iterative process allows for continuous improvement and learning from each casting experience.

Overall, casting solid propellant into a solid propellant grain requires precision, attention to detail, and a willingness to make adjustments based on the results. The ultimate goal is not only to achieve optimal performance but also to refine the casting process and enhance future designs [47][45].

4.6 Powder Handling and Storage

Produced powder, including solid propellant grain, is characterized by extreme reactivity and requires careful storage to maintain a safe workspace. In order to ensure a safe environment, both loose powder and solid propellant grain should be stored in fire-resistant/non-combustible units. This is particularly important for solid rocket propellants as they can be highly reactive and sensitive to various substances such as acids, nitrates, sulphates, halogens, peroxides, and alkalis. Additionally, solid propellant grains may be sensitive to water after prolonged contact [48]. Even though Sahara Desert contains about 100 times more water than the Moon, it is still of a great challenge to fully comprehend its behaviour. It was thought of water to evaporate on the sunlit surface, but that turned out not to be the case. It makes powder - water prevention even more difficult and needs to be treated with utmost caution [49].

The storage facility for solid propellant grain should adhere to certain precautions, similar to those for loose powder storage. The storage area should be well-ventilated, even though the atmospheric conditions on the Moon may differ from those on Earth. Broad passageways should be maintained to ensure easy access to the storage containers. It is crucial to keep the storage unit clean in order to prevent dust from accumulating on the floors, walls, and containers [49].

Containers used for storing solid propellant grain should be perfectly sealed to prevent any exposure to the atmosphere, and they should be kept in cool places away from direct sunlight [48]. Furthermore, the lack of atmosphere on the Moon poses additional challenges due to the electrostatically charged nature of its soil. The gases present on the Moon's surface form a thin layer in its exosphere, where they can become electrically charged. This leads to the formation of problematic moon dust which can be abrasive and clingy. It is important to keep solid propellant grain away from moon dust, as it could potentially react and cause explosions. The containers used for storing solid propellant grain should be designed to withstand the abrasive nature of moon dust and should have robust vacuum seals [50]. Gases present on the Moon form a thin layer on the surface contained in the so-called exosphere. During the day the UV sunlight provides enough energy to eject electrons from those gases, which give them electrical charge. As a result, they can float over 1500m from the ground. During the night, on the other hand, solar wind comes in providing electrons and the gas settles on the surface once again. This operation is a source of a very problematic moon dust. Apollo astronauts describe it as *gritty, abrasive and clingy. It can wreak havoc on equipment and computers. Moonwalkers were coated in it and their spacesuits were almost threadbare when they returned to Earth [51].* This is an important factor in handling the nano aluminum powder, as it is crucial to keep it away from anything that could potentially react with it and cause explosion. Additional caution needs to be given to the containers in which the powder is stored as it was reported that the dust destroyed the vacuum seals of Apollo sample containers [50].

In addition to these precautions, any energy source, such as power generators for machinery or ventilation systems, should be handled with utmost caution as it can potentially ignite the aluminum powder and oxygen present in the lunar regolith. Therefore, comprehensive safety measures should be implemented to minimize the risk of ignition and explosion [48].

In summary, the storage of solid propellant grain requires similar precautions as the storage of loose powder. Fire-resistant/non-combustible storage units should be used, and the storage area should be well-ventilated. The storage containers should be sealed to prevent atmospheric exposure, stored in cool places away from direct sunlight, and designed to withstand the abrasive nature of moon dust. Additionally, all energy sources should be handled carefully to prevent ignition. By following these guidelines, a safe storage environment can be ensured for solid propellant grain in a Moon-based facility. Below, an example of a storage unit facility on the Moon can be seen.

Figure 20: Storage facility building for powder containers AI generated [52]

5 Fuel Combustion

5.1 Solid Rocket Motor

Solid and powdered propellants were used in the rocket motor, up until the liquid propellant rockets were invented in the 20th century. As the latter was more efficient and controllable it quickly overtook the former. Nonetheless, thanks to the advancements in the solid propellants such as novel additives and a use of nanometals they still remain an exceptionally attractive option [53]. If it comes to orbital rockets there is a clear division in the type of fuel used, i.e; to launch small payloads to orbital velocities solid rockets are used, while for larger orbital rockets liquid fuel is preferred. But even then they often use solid rocket boosters for initial thrust [54]. Choosing a rocket motor is not an easy task as the working principles of a solid rocket motor are highly complex. To perform the crucial analysis however, some assumptions can be made to simplify the calculation while keeping an adequate picture of the motor. The ideal rocket motor hypothesis is an excellent way to reduce the complexity of analysis without compromising to adequacy of the model. Ideal rocket motor is characterized by:

- complete propellant combustion
- combustion products follow the ideal gas law
- no friction influencing the flow of exhaust products
- adiabatic system
- steady-state conditions
- uniform expansion of working fluid
- one-dimensional and non-rotational flow
- flow velocity, pressure and density uniform across the nozzle area
- frozen equilibrium conditions
- propellant burning uniformly, perpendicular to the burning surface over the entire surface exposed to combustion [55]

A schematic of a solid propellant rocket motor can be seen below in figure 21. The outer layer of the motor in the aluminum-made casing, confirming the initial findings of aluminium being widely used in the space industry. And while it is not the topic of this thesis to design the motor case, Jackson Stephenson had done an excellent analysis in his paper titled "Design of Nozzle for High-Powered Solid Rocket Propellant" [56]. In his paper, Stephenson considers the longitudinal and diametrical expansion, Young's modulus, as well as Poisson's ratio of the 10-foot-long 6 ID x 6.5" OD tubing composed of 6061-T6 Aluminum. This material commonly used as motor casing thanks to its high strength and relatively low weight. The max allowable pressure for 1/4" and 1/2" thickness can be found in Appendix A and are 588.235 and 1176.471, respectively.

Fuel and oxidizer are stored in the propellant grain. Once an electrical signal is sent to the igniter it creates high pressure gases that in change ignite the main propellant grain. Created energy must be then converted via the nozzle into a useful work, or thrust, making the nozzle one of the most important parameters of the rocket design. The nozzle used in a solid rocket motor is a supersonic converging-diverging nozzle. The gas travels from the combustion chamber through the converging part of the nozzle. Due to the decreasing section of the motor, the gas starts accelerating until it reaches the speed of sound at the nozzle's throat. After passing to the diverging part, the velocity is so high that it gives momentum to the motor. The outlet velocity is higher than the speed of sound.

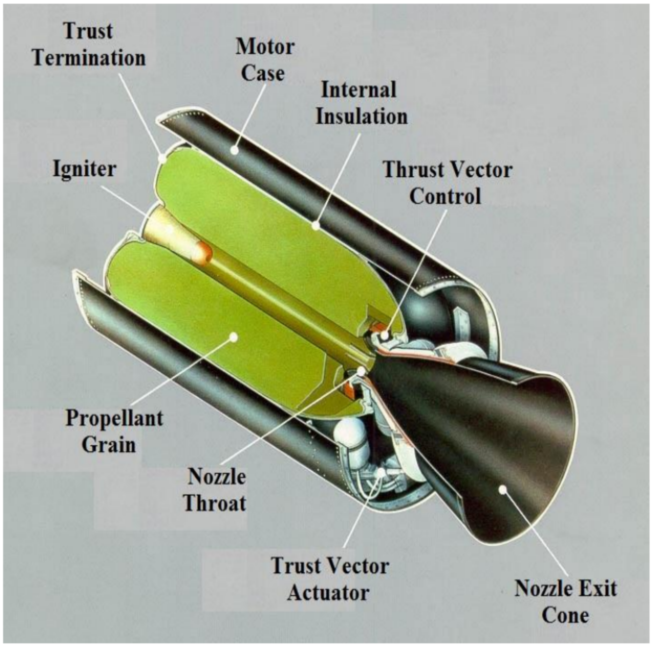


Figure 21: solid propellant rocket motor [57]

In the solid rocket motors the fuel can be either a cast or free standing. The cast propellant is prepared from a highly viscous liquid. After being poured inside the motor case it is "baked", allowing the fuel to plasticize. Free standing propellant on the other hand, are poured inside molds rather than directly into the motor. The propellant can also be categorized based on the grains geometry. In this type of motor the grain refers to blocks where the propellant is stored. The grain is cylindrical by default due to its fit to the rocket motor and the maximized volumetric efficiency. Large motors use segmented grains, while the smaller ones suffice with one grain only. The cross-section, on the other hand, has multiple options available and is a defining element of the thrust-time profile [57][58]. The visualisation of the solid propellant grain categories can be seen in the scheme below.

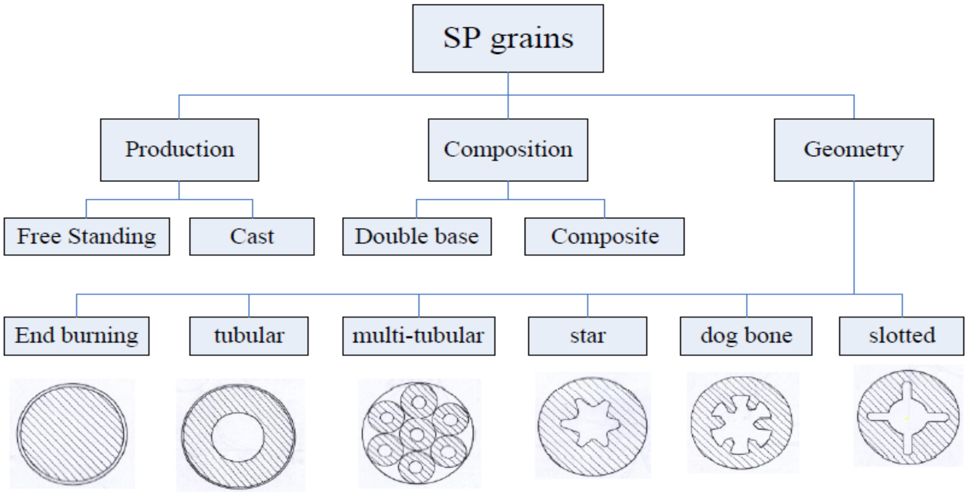


Figure 22: Solid propellant grains [57]

Below, in figure 23, the thrust curves for different solid propellant grains are present.

One of the categories present above is composition which can be either dual base or a composite. Composite propellants are the prevalent ones in solid motors, and are made of more than one substance bonded together by the binder. Double base propellant, on the other hand, is a mix of of two kinds of base propellants with a chemical binding between the oxidiser and fuel. The oxidiser and the fuel are of the same molecule chain [57]. ALICE propellant consist solely of nano-aluminium and water making it a double base propellant.

Small rockets consists of a single grain, while the bigger ones can have multiple segments. The visualisation can be seen in figure 24. The inhibited surface is a protective coating that can withstand high temperatures, ensuring that propellant surfaces shielded by the inhibitor remain unignited throughout the entire motor's functioning period [60]

To obtain the geometry of the grain, the equations 2 and 3 are used.

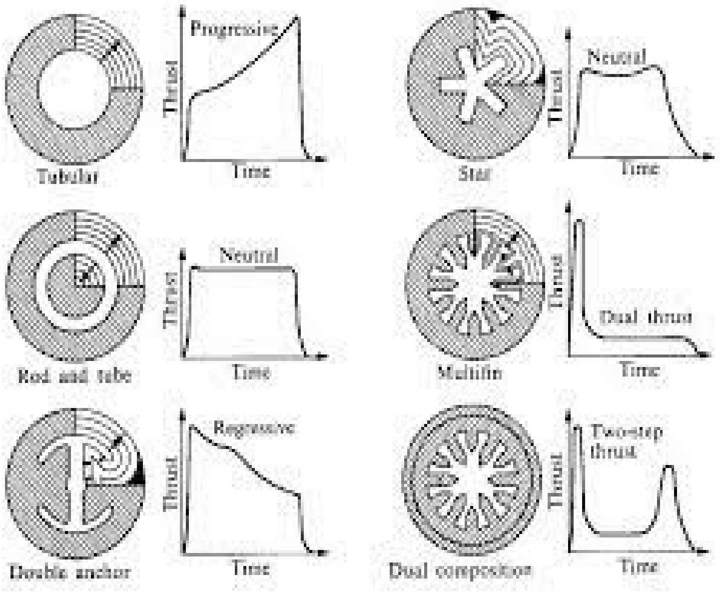


Figure 23: Solid propellant grain thrust curves [59]

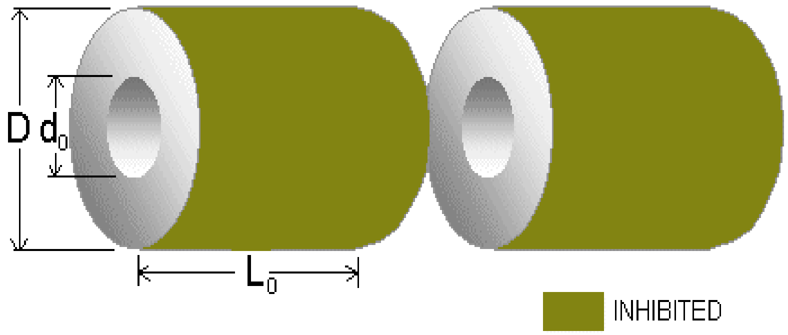


Figure 24: solid propellant grains [60]

$$SolidPropellantGrainVolume = \pi \cdot L_0 \cdot \frac{D^2 - d_0^2}{4} \tag{2}$$

$$SolidPropellantGrainBurnSurface = \pi \cdot d_0 \cdot L_0 + \frac{pi}{2} \cdot (D^2 + d_0^2) \tag{3}$$

5.2 Nozzle Design

Having identified the type of rocket motor and the grain type, the nozzle parameters are calculated to be further used in the propellant testing. As mentioned before, the nozzle design is of paramount importance as it is responsible for for providing enough energy to take off. This energy refers to the thrust, which is expressed with the following equation:

$$F = \dot{m} \cdot g \cdot I_s p \tag{4}$$

where $\dot{m}$ is the mass flow rate through the nozzle exit, g is the gravitational constant and I_{spe} is the specific impulse and they all can be calculated using the equations below.

$$I_{sp} = \frac{V_e}{g} \tag{5}$$

$$\dot{m} = \frac{A_t \cdot P_c}{\sqrt{T_c}} \cdot \sqrt{\frac{\gamma}{R}} \cdot \left(\frac{\gamma+1}{2}\right)^{-\frac{\gamma+1}{2(\gamma-1)}} \tag{6}$$

$$V_e = M \cdot \sqrt{\gamma \cdot R \cdot T_e} \tag{7}$$

$$A_e = A_t \cdot \sqrt{\frac{1}{M}\left(2 + (\gamma-1) \cdot M^2\right)\left(\frac{\gamma+1}{\gamma-1}\right)^{\frac{\gamma+1}{\gamma-1}}} \tag{8}$$

Mach number, necessary to obtain both the exit nozzle area and the exit velocity, can be calculated using the following formula

$$M = \sqrt{\left(\frac{P_e}{P_c}\right)^{\frac{1-\gamma}{\gamma}} - 1}\left(\frac{2}{\gamma-1}\right) \tag{9}$$

Furthermore, the exit temperature can be be calculated using equation 9

$$T_{\mathrm{E}} = \frac{T_{\mathrm{c}}}{1 + \frac{\gamma-1}{2} \cdot M^2} \tag{10}$$

In addition to the equations above, to adequately assess the performance of the nozzle the burn rate can be described using equation 11.

$$r = a \cdot Pc^n \tag{11}$$

Where a and n are the propellant burning rate coefficients. In the table below, the values for burn rate coefficient and exponent are listed, together with γ which represents the specific heat ratio, fuel equivalence ratio ϕ as well as aluminium density.

Parameter	**Value**
burn rate coefficient a	0.70274
burn rate exponent n	0.57019
γ	1.13
ϕ	0.71
ρ_{Al} [g/cm3]	2700
$\rho_{oxydizer}$ [g/cm3]	1770
volume fracture of aluminium to water x	0.7

6 Testing

Recycling of space debris is a complex process combining multiple operations. To enhance the efficiency and precision of this study a Python Graphical User Interface (GUI) dashboard was developed. It serves as the central hub, bringing together various critical processes and data streams into one coherent platform.

The primary objective of the dashboard is to offer a holistic view of the solid rocket motor development process. It is divided into 2 tabs, the first one dedicated for the solid propellant grain's geometry and the second one for the motor launch parameters using the ALICE propellant.

Once the amount of aluminium available for recycling is inserted, the user have to choose the solid propellant grain geometry. Then the system calculates the amount of powder obtained in the Inert Gas Condensation process, assuming the process efficiency of 90% [38]. Subsequently, using the equivalence ratio with the reaction 1 and combining it with the equation below the dashboard displays the amount of water needed to produce ALICE propellant.

$$phi = \frac{\text{fuel-to-air ratio}}{\text{stoichiometric fuel-to-air ratio}} \tag{12}$$

Having introduced the geometry of the tubular solid propellant grain, the dashboard uses equations 2 and 3 to calculate the volume of the solid propellant grain and its burning surface. Knowing the densities of nanoaluminium and oxidizer (water), the propellant density can be calculated using equation 13.

$$\rho_{propellant} = (x \cdot \rho_{al}) + ((1 - n) \cdot \rho_{oxidizer}) \tag{13}$$

Once the density is known, the program calculates the volume of the propellant and thanks to that it can display the information regarding how many solid propellant grains can be filled with ALICE propellant.

information about the powder available after the IGC as well as the water needed are displayed to the user. Moreover, the information about the solid grains produced with the available amount of aluminium is presented. The second tab, on the other hand, focuses on the nozzle parameters. As discussed before, the nozzle is a converging - diverging one. After choosing the desired chamber pressure and temperature as well as the throat nozzle area, the user can see all the parameters calculated using equations from the previous chapter.

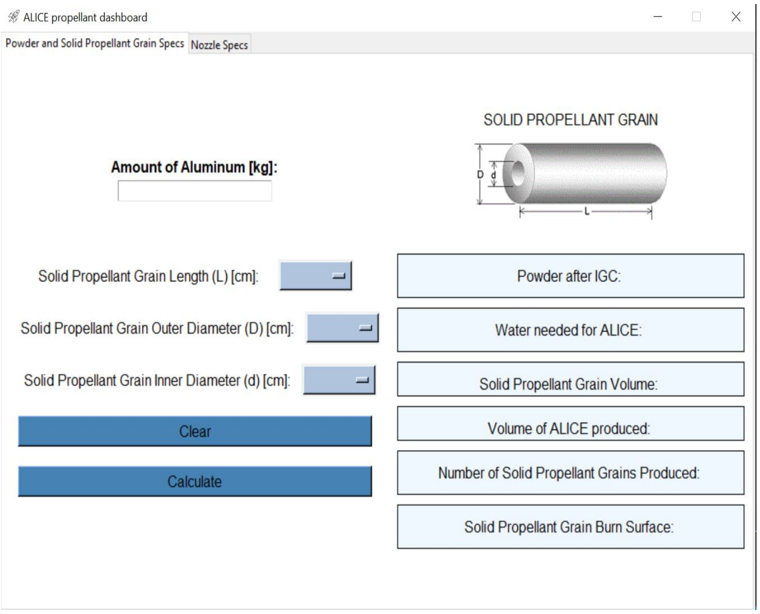


Figure 25: Propellant dashboard tab 1

The second tab, on the other hand, focuses on the nozzle parameters and the motor's launch performance using ALICE propellant. As discussed before, the nozzle is a converging - diverging one. First, the user needs to choose the parameters regarding the nozzle throat area, as well as the chamber pressure and temperature. The, using equations 8, 7 and 9 the program calculates the nozzle exit area, exit velocity and Mach number, respectively. Furthermore, combining the nozzle design with the fuel parameters equations 6, 11, 5 and 4 are used to calculate the mass flow rate through the nozzle, burn rate, specific impulse and thrust, respectively.

This multifaceted approach allows making data-driven decisions with ease and accuracy. One of the remarkable achievements of this study is the ability to combine all the steps, from collecting of the debris to burning it as a propellant, in one user-friendly dashboards. This predictive power enhances the ability to optimize rocket motor designs, leading to more efficient and reliable propulsion system.

What further validates this methodology is its alignment with experimental data. The results obtained through the dashboard consistently correlate with data gathered from experiments conducted using similar fuel composition. This not only validates the reliability of the predictive model but also highlights the potential practical approach of the findings in the development of solid propellant rocket motor.

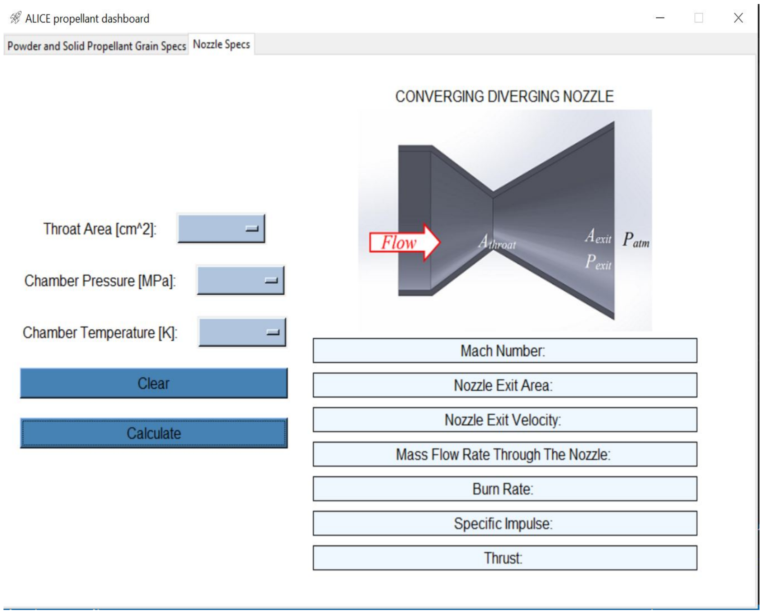


Figure 26: Propellant dashboard tab 2

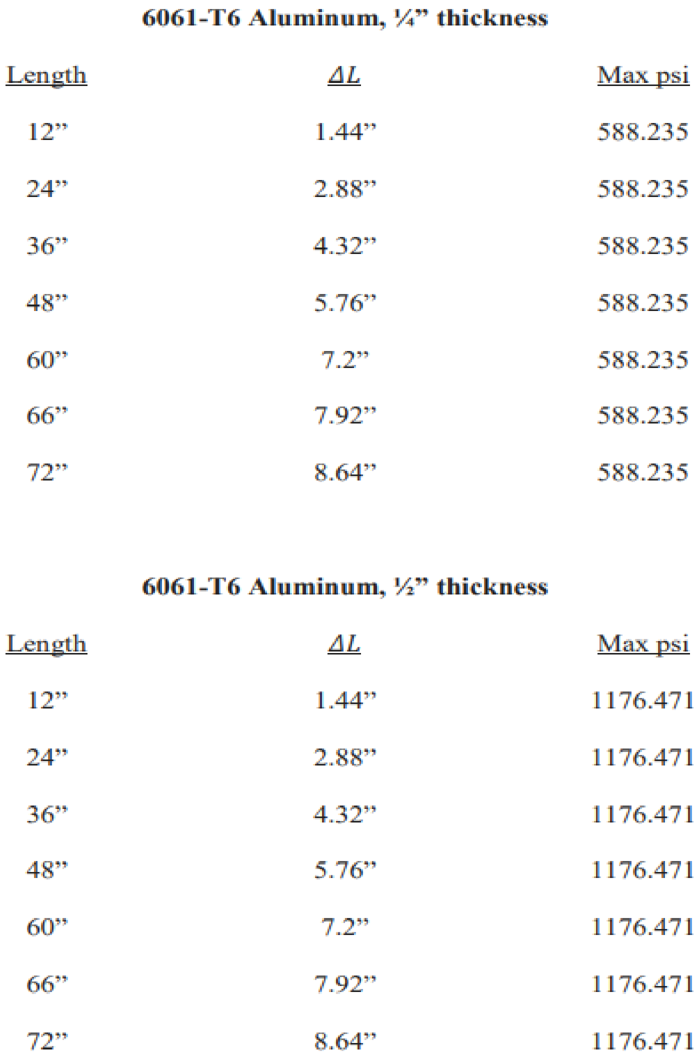
7 Conclusions

In conclusion, the establishment of a recycling station on the Moon, with its abundant reserves of aluminium, promises significant benefits for both the space industry and the planet as a whole. The exceptional recycling potential of aluminium not only ensures a constant supply of this material in the future but also offers a solution to the growing issue of debris in low Earth orbit. By harnessing the power of recycling, the probability of Kessler's syndrome and collisions with debris during new launches can be greatly decreased.

Furthermore, the Moon presents an ideal location for such a recycling station, given its vast space and proximity to the Earth. With ample room for expansion, this lunar facility could become a pivotal hub for future space exploration and serve as a foundation for upcoming endeavors, including potential Martian settlements. Additionally, the Moon's accessibility to direct solar energy enables a sustainable energy source to power these endeavors when sunlight is available.

By tapping into the Moon's potential, we can not only ensure a constant supply of aluminium and reduce the environmental impact of space exploration but also pave the way for a future that encompasses safe and sustainable travel across and beyond our celestial neighbor. The recycling station on the Moon holds the keys to preserving our planet, while attaining uncharted heights in our quest for knowledge and expansion in the cosmos.

8 Appendix A



6061-T6 Aluminum, ¼” thickness

Length	ΔL	Max psi
12”	1.44”	588.235
24”	2.88”	588.235
36”	4.32”	588.235
48”	5.76”	588.235
60”	7.2”	588.235
66”	7.92”	588.235
72”	8.64”	588.235

6061-T6 Aluminum, ½” thickness

Length	ΔL	Max psi
12”	1.44”	1176.471
24”	2.88”	1176.471
36”	4.32”	1176.471
48”	5.76”	1176.471
60”	7.2”	1176.471
66”	7.92”	1176.471
72”	8.64”	1176.471

Figure 27

9 Appendix B

Different assembly stages of solid propellant rocket motor and CAD drawings

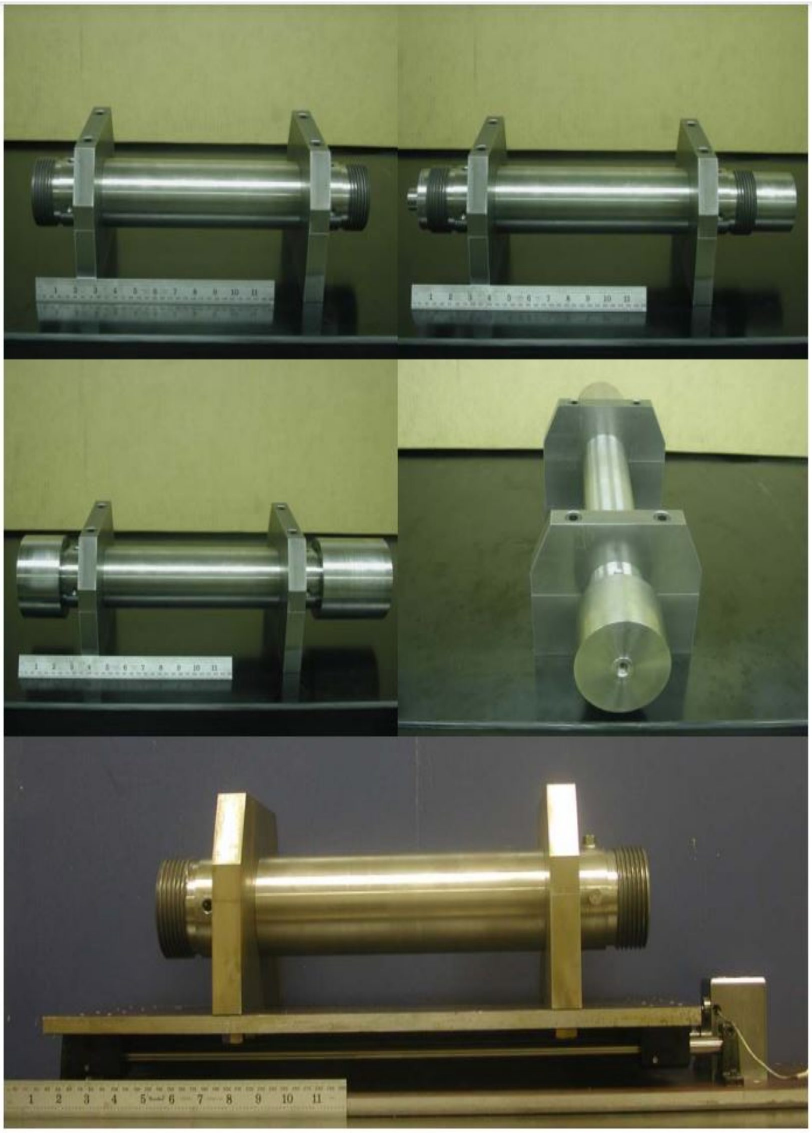


Figure 28

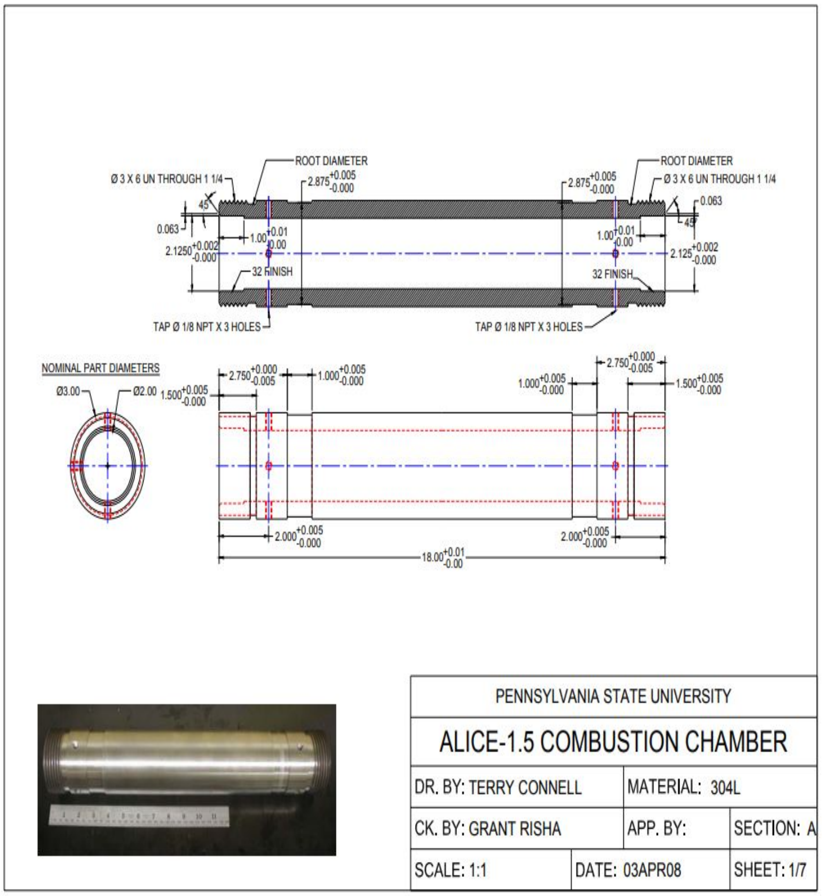
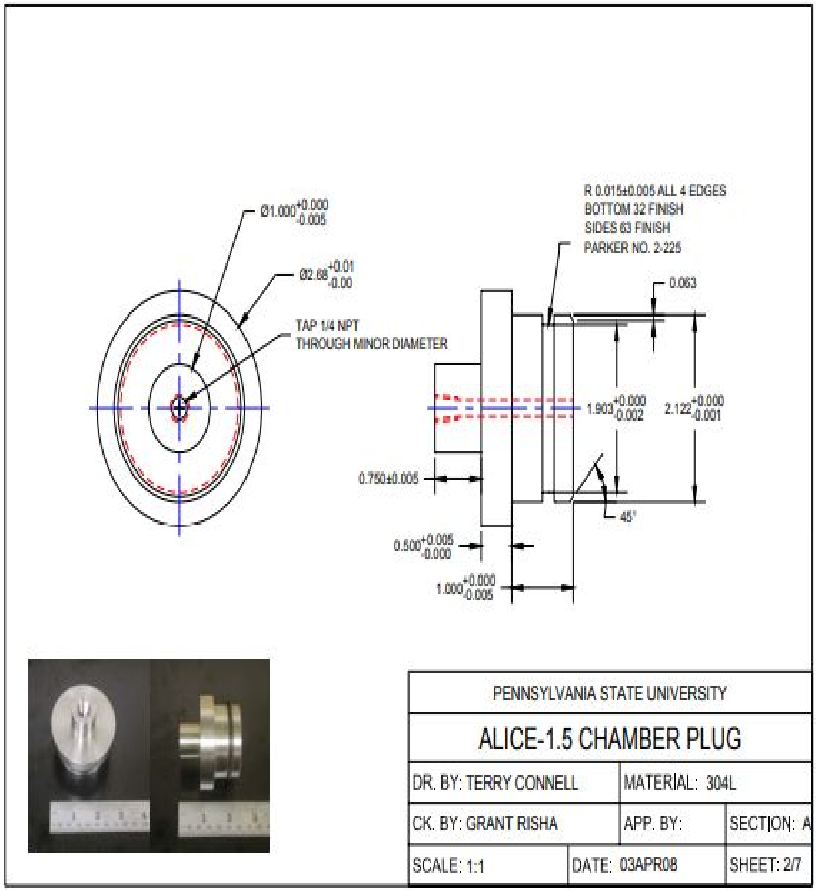

ROOT DIAMETER
Ø 3 X 6 UN THROUGH 1 1/4
2.875 +0.005 -0.000
45°
0.063
1.00 +0.01 -0.00
2.1250 +0.002 -0.000
2.125 +0.002 -0.000
32 FINISH
TAP Ø 1/8 NPT X 3 HOLES
NOMINAL PART DIAMETERS
Ø3.00
Ø2.00
1.500 +0.005 -0.000
2.750 +0.000 -0.005
1.000 +0.005 -0.000
2.000 +0.005 -0.000
18.00 +0.01 -0.00
PENNSYLVANIA STATE UNIVERSITY
ALICE-1.5 COMBUSTION CHAMBER
DR. BY: TERRY CONNELL
MATERIAL: 304L
CK. BY: GRANT RISHA
APP. BY:
SECTION: A
SCALE: 1:1
DATE: 03APR08
SHEET: 1/7

Figure 29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Ø2.68 +0.01 -0.00
TAP 1/4 NPT
THROUGH MINOR DIAMETER
R 0.015±0.005 ALL 4 EDGES
BOTTOM 32 FINISH
SIDES 63 FINISH
PARKER NO. 2-225
0.063
1.903 +0.000 -0.002
2.122 +0.000 -0.001
0.750±0.005
45°
0.500 +0.005 -0.000
1.000 +0.000 -0.005
PENNSYLVANIA STATE UNIVERSITY
ALICE-1.5 CHAMBER PLUG
DR. BY: TERRY CONNELL
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CK. BY: GRANT RISHA
APP. BY:
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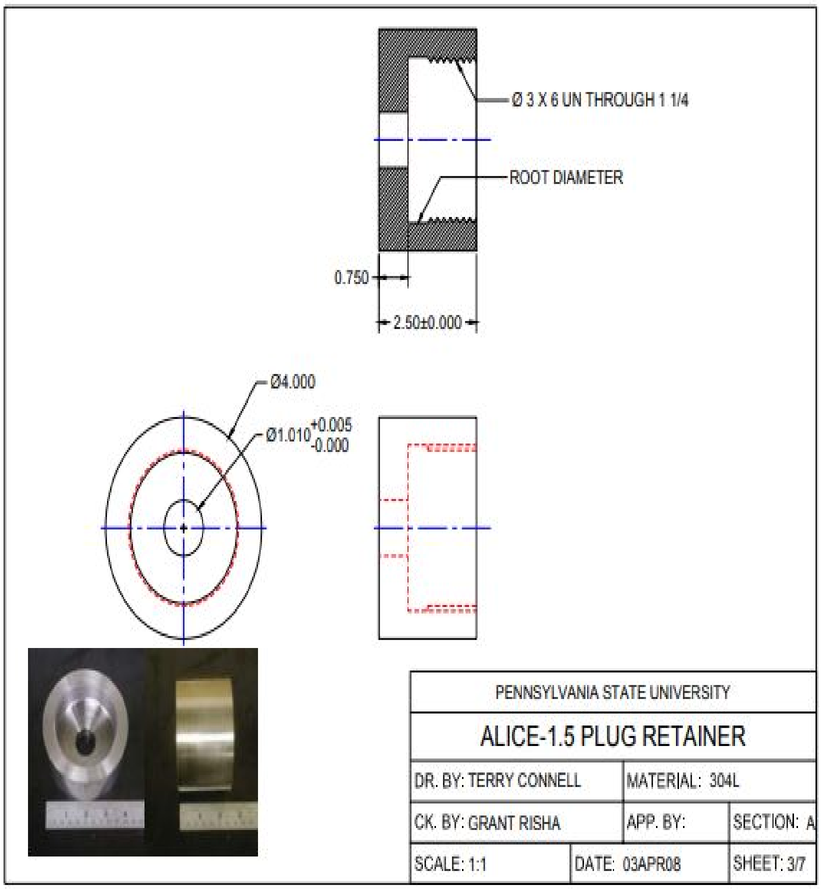
SHEET: 2/7

Figure 30: [61]


Ø 3 X 6 UN THROUGH 1 1/4
ROOT DIAMETER
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Ø4.000
Ø1.010 +0.005 -0.000
PENNSYLVANIA STATE UNIVERSITY
ALICE-1.5 PLUG RETAINER
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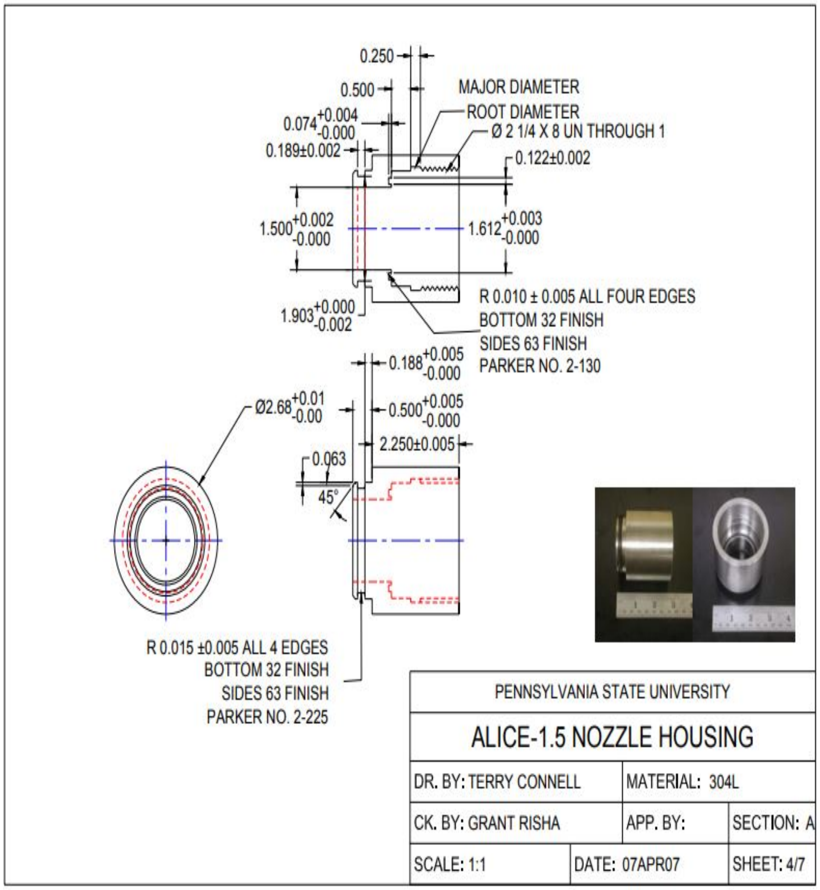
Figure 31: [61]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0.500
MAJOR DIAMETER
ROOT DIAMETER
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Ø 2 1/4 X 8 UN THROUGH 1
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0.122±0.002
1.500 +0.002 -0.000
1.612 +0.003 -0.000
R 0.010 ± 0.005 ALL FOUR EDGES
BOTTOM 32 FINISH
SIDES 63 FINISH
PARKER NO. 2-130
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0.188 +0.005 -0.000
Ø2.68 +0.01 -0.00
0.500 +0.005 -0.000
2.250±0.005
0.063
45°
R 0.015 ±0.005 ALL 4 EDGES
BOTTOM 32 FINISH
SIDES 63 FINISH
PARKER NO. 2-225
PENNSYLVANIA STATE UNIVERSITY
ALICE-1.5 NOZZLE HOUSING
DR. BY: TERRY CONNELL
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APP. BY:
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SHEET: 4/7

Figure 32: [61]

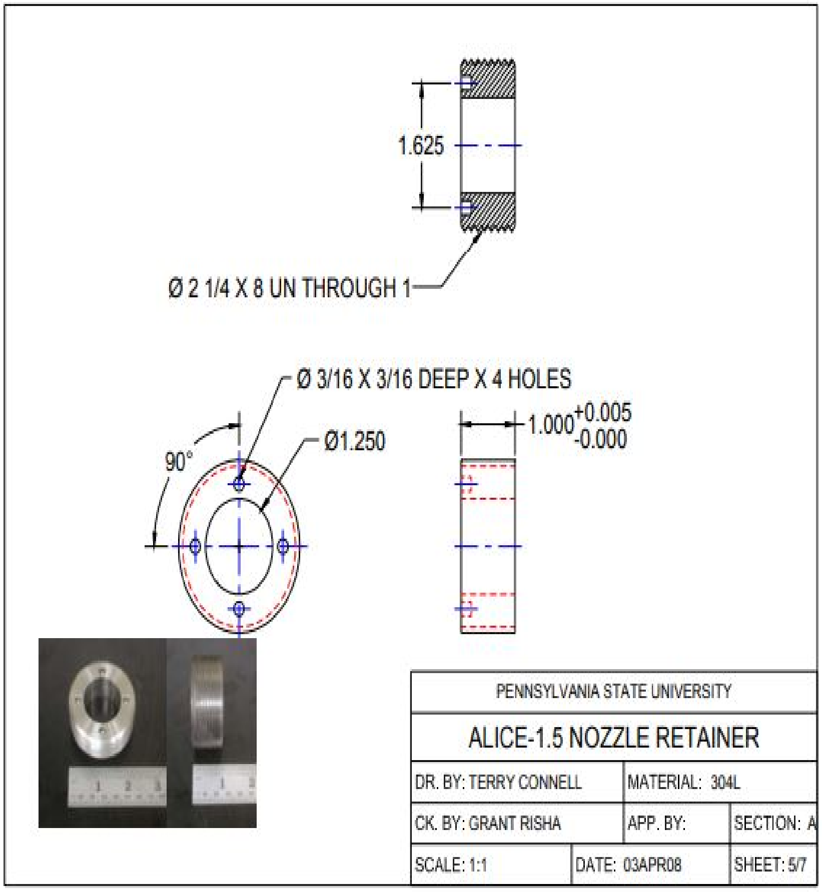
1.625
Ø 2 1/4 X 8 UN THROUGH 1
Ø 3/16 X 3/16 DEEP X 4 HOLES
90°
Ø1.250
1.000 +0.005 -0.000
PENNSYLVANIA STATE UNIVERSITY
ALICE-1.5 NOZZLE RETAINER
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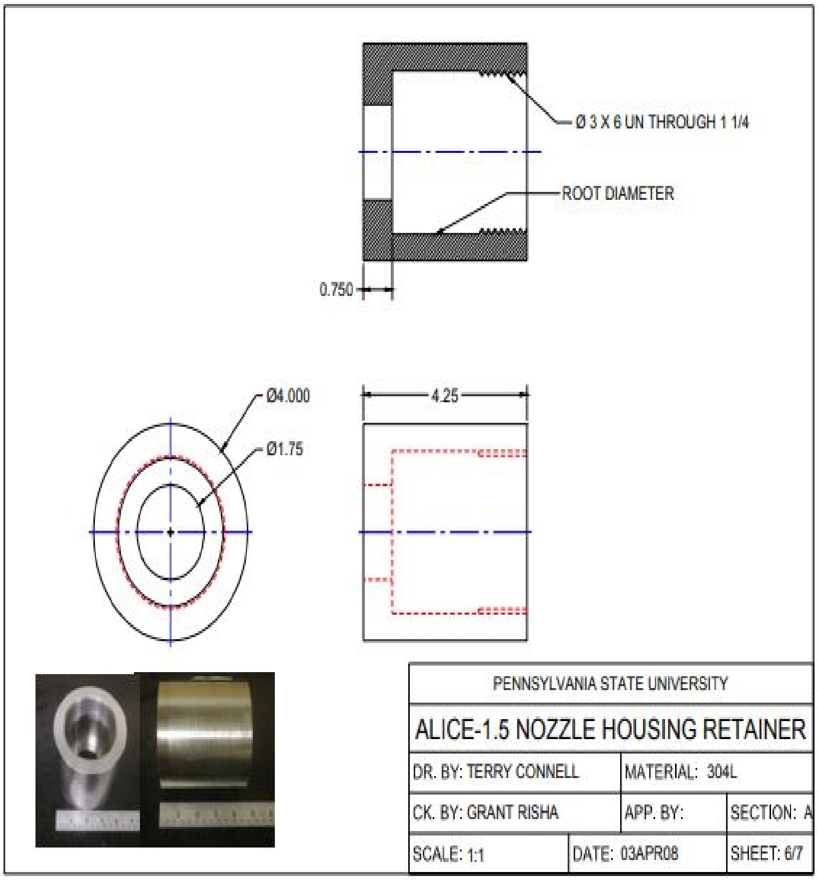
Figure 33: [61]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ROOT DIAMETER
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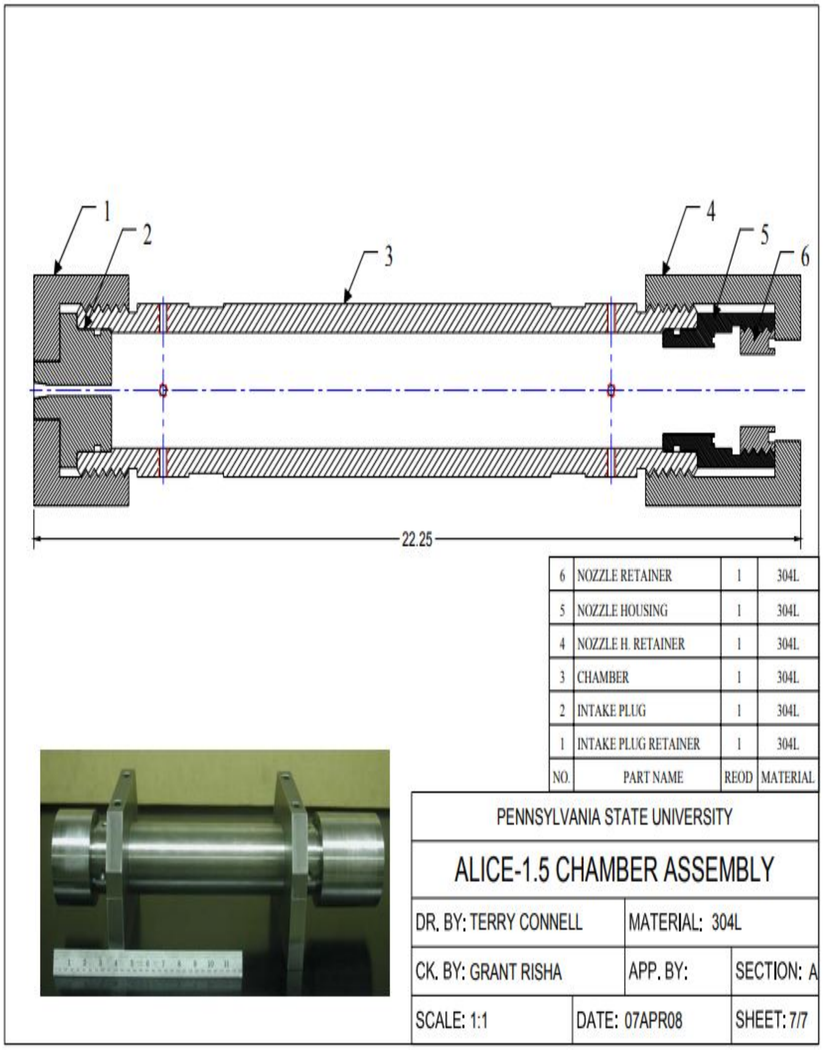
Figure 34: [61]



NO.	PART NAME	REQD	MATERIAL
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5	NOZZLE HOUSING	1	304L
4	NOZZLE H. RETAINER	1	304L
3	CHAMBER	1	304L
2	INTAKE PLUG	1	304L
1	INTAKE PLUG RETAINER	1	304L

PENNSYLVANIA STATE UNIVERSITY

ALICE-1.5 CHAMBER ASSEMBLY

DR. BY: TERRY CONNELL	MATERIAL: 304L	
CK. BY: GRANT RISHA	APP. BY:	SECTION: A
SCALE: 1:1	DATE: 07APR08	SHEET: 7/7

Figure 35: [61]

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