ALUMINUM POWDER COMBUSTION

2023 GATEWAYS TO BLUE SKIES: CLEAN AVIATION ENERGY COMPETITION

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Abstract

This report addresses the challenge posed by NASA's 2023 Gateways to Blue Skies: Clean Aviation Energy Competition for which our team must propose an alternative, zero or close-to-zero emissions energy source. Our team has analyzed the carbon footprint of the production and combustion of current-day jet fuel (Jet A), where it was found that the majority of emissions are produced during combustion. The team decided that direct combustion of aluminum powder is the best alternative energy source to meet the competition guidelines. Our team then compared aluminum powder to Jet A and assessed the consequences of different combustion characteristics and aluminum nanoparticle diameters. Overall efficiency calculations demonstrate that aluminum fulfills the energy density requirements while also producing no harmful emissions except for aluminum oxide (Al_2O_3) and trace amounts of aluminum nitride (AlN), both of which can be captured easily. Current aluminum supply chain metrics were collected, analyzed, and compared to the team's proposed close-to-zero emissions process. The entire process of collecting raw material up to the powderization of aluminum is described, with the team's proposed changes being outlined throughout the paper. Modifications to allow for aluminum powder combustion in current gas turbine engines are outlined and potential solutions and their current readiness levels are listed in order to justify the feasibility of such changes. Increases in aluminum production and infrastructural changes needed to keep up with the recycling of captured alumina is discussed, outlining the aluminum production rates needed to reach the necessary fuel supply by 2050. The need for new engine modifications, research and development, and infrastructural growth is shown in a timeline, providing a general overview of when important milestones should be achieved.

The direct carbon emissions released from the team's proposed process demonstrates a 96% decrease without having to drastically change the current aluminum production process. The selection of a set range of particle diameters allows for the aluminum powder to be safely handled without the worry of combusting in air unintentionally, ensuring safe handling from start to finish. An analysis of previous aluminum powder combustion studies, necessary infrastructural changes, and technological advancements provides the team with a strong foundation to claim that the use of aluminum powder as a clean aviation energy source is both feasible and viable by the year 2050.

1. Introduction

With over 4 billion passengers carried in 2019 and supporting around \$3.5 trillion in world economic activities, the aviation industry has a significant impact on society [1], [2]. However, due to the COVID-19 pandemic, enplanements fell 40% from 2019 to 2020, and a full recovery is not expected until the end of 2023 [3], [4]. Along with this drop in passengers, a subsequent 43% drop in the aviation industry's CO_2 emissions occurred [4]. Nonetheless, the Federal Aviation Administration has projected a 185% increase in enplanements from 2020 to 2050, reaching over 1 billion enplanements in the United States alone [3]. Carbon emissions will begin to rapidly outpace technological advancements unless significant changes are made.

Using data from The Airline Data Project (ADP), which was established by the MIT Global Airline Industry Program, the average flight time for commercial airlines was calculated to be 2.39 hours (see Appendix D), categorizing the average flight as a short-haul flight [5]. The team is expecting short-haul flights to continue to dominate the aviation industry in 2050, while passengers and flight frequency will continue to increase [5]. With over 60 billion liters of Jet A fuel consumed per year, the aviation industry releases around 920 million metric tonnes (MT) of CO_2 into the atmosphere annually, accounting for 2.4% of global emissions and having increased by 30% from 2013 to 2019 [6], [7]. Table 1 outlines the carbon emissions associated with the production of Jet A fuel, demonstrating that the combustion of Jet A fuel accounts for 83% of CO_2 emissions in the entire process [9], [10]. In order to solve the growing problem of aircraft CO_2 emissions, the discovery of a new clean aviation energy source will need to be implemented.

Table 1: Jet A Production Emissions.

Jet A	**CO_2 Emissions (kg CO_2/kg Jet A)**
Crude Oil Production	0.37
Refining	0.19
Transportation	0.08
Combustion	3.18
TOTAL	3.82

Sources: [7], [10], [31].

2. Metrics of Aluminum Powder Combustion

In Table 2, the relative mass energy density (specific energy) and volumetric energy densities (energy density) of both aluminum and standard Jet A are shown. The chosen aluminum particle diameter ranges from 50 nm to 50 µm in order to stay above the critical particle diameter that causes pyrophoricity (i.e., spontaneous combustion in air) and high particle oxidation rates, and below the maximum particle size above which burn rate drops significantly below 100% [11], [12]. The values in the table are stated for a particle diameter of 11.7 µm, but the values would be similar for any particle in the chosen diameter range. The energy density of such aluminum, as well as its thermal efficiency, are both significantly higher than that of Jet A, whereas the specific energy of aluminum is lower. These factors combine to yield only a small overall decrease in effective specific energy while increasing the overall efficiency by around 11% for our proposed solution. Additionally, the total mass of fuel burned for our proposed energy source is approximately 11% higher than for a comparable flight powered by Jet A. This small decrease in effective specific energy and increase in fuel mass burned is the cost of switching to a fully renewable fuel system by 2050. As shown in Table 2, this fully renewable fuel system will achieve a 96% reduction in emissions as a result of implementing new aluminum production technologies, transitioning to clean renewable energy, and electrifying transportation around the world. The numbers here include both direct and indirect emissions, both of which are discussed in further detail in the following sections.

Table 2: Energy Density/Efficiency Comparison.

	Jet A	**Al Particles of Diameter Between 50 nm and 50 μm (11.7 μm)**	**Percent Difference Relative to Jet A**
Energy Density	34.5 MJ/L[34]	80.0 MJ/L[36]	+131%
Specific Energy	43.0 MJ/kg[33]	30.0 MJ/kg[36]	–30%
Thermal Efficiency	50%[32]	64%[35]	+14%
Propulsive Efficiency	75%[32]	75%[32]	0%
Overall Efficiency	37.5%	48%	+11%
Effective Energy Density	12.9 MJ/L	38.4 MJ/L	+198%
Effective Specific Energy	16.1 MJ/kg	14.4 MJ/kg	–11%
Mass of Fuel Consumed	24 MT/Flight[Appendix A]	26.9 MT/Flight[Appendix A]	+11%
Total Yearly Emissions	**920 MMT CO_2**	**42 MMT CO_2[Appendix F]**	**–96%**

Note: MMT = million metric tonnes.

3. Aluminum Supply Chain Processes

The creation of our proposed aluminum powder is a complex process. It starts out by mining raw bauxite, converting the bauxite to alumina (or aluminum oxide, or Al_2O_3), converting the alumina to pure aluminum, and then powderizing the aluminum into particles on the nano-micro scale. The process of turning bauxite into alumina is fairly detailed and is referred to as the Bayer Process [8]. It is a sound process that has been used for decades, and we do not foresee any remarkable changes to this process by 2050. A process map depicting this method can be seen in Fig. G.1 in Appendix G.

Fig. 1 shows a process map for the Hall–Héroult and Inert Anode Hall–Héroult smelting processes to convert alumina to pure aluminum. Alumina can come from the Bayer process, but it may also be taken from the residuals of the powder combustion in a jet engine and be a part of the recycling process. The boxes outlined in green denote the only parts of the process that differentiate the Hall–Héroult process from the Inert Anode Hall–Héroult process, which comprise the current and proposed alternative aluminum production methods, respectively. Switching to the inert anode method is how the main harmful emissions are cut out of the process, but this new technology comes at the cost of a larger necessary energy input. CO_2, CF_4, and C_2F_6 are released as byproducts in the traditional Hall–Héroult, whereas in the Inert Anode Hall–Héroult, only O_2 is released from the chamber and can be captured if desired [14]. In either process, the alumina is heated to a molten state and mixed with cryolite in an electrolysis chamber. A carbon anode for the traditional Hall–Héroult or an inert (possibly made of SnO_2) anode for the Inert Anode Hall–Héroult is then inserted into the mixture. Both processes use similar cathodes [13]. A high current is

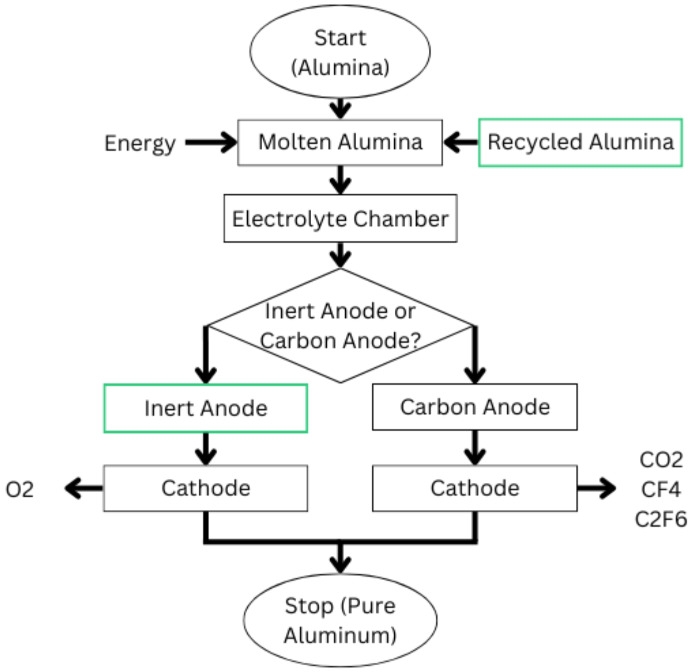


Figure 1: Process map describing the Hall–Héroult and Inert Anode Hall–Héroult smelting process.

passed through the electrolysis chamber (from the cathode to the anode), and the pure aluminum is collected on the cathode. Inert Anode Hall–Héroult requires a higher current compared to the carbon-intensive Hall–Héroult method, which is where the extra energy is needed.

The final process is the atomization of aluminum. The aluminum is heated to a molten state and then combined with high-pressure gas or water, which cools the aluminum into small particles by spraying it. The powder is then filtered by diameter, and assuming the diameter is in the proposed range, it can be stored in any container that is convenient and non-porous. During the atomization process, the particles are naturally passivated, meaning that they are non-pyrophoric, which leads to completely safe handling in air [15]. This is due to a thin oxidation layer that forms on the outside of each particle (approximately 2 to 3 nm thick), which has a minimal effect on the thermal efficiency of the aluminum powder combustion, still allowing for a nearly full burn. The volume fraction of the passivation layer to pure aluminum underneath being so small is what allows this. As the particles exceed 100 nm in diameter, the volume fraction of Al_2O_3 to Al nears 0% [15]. At our proposed particle diameter range of 50 nm to 50 μm, we can take the volume fraction to be negligible. Fig. G.2 in Appendix G shows a process map describing the above method.

The only major technological innovation that our team has proposed for this part of the supply chain is the inert anode used in the Hall–Héroult process, something that is already being implemented in the aluminum smelting industry. Two companies, ELYSIS (a joint venture between Alcoa and Rio Tinto) [37] and RUSAL [38] have already begun implementing this technology in their smelters. Both companies have pledged to achieve net-zero smelting by 2050 using inert anode technology retrofitted into their current smelters.

4. Aluminum Supply Chain Emissions Analysis

Tables 3 and 4 demonstrate the key metrics of each step in the aluminum supply chain for the current process and the proposed process, respectively. In our proposed process, smelting is slightly more efficient and the smelting and atomization are both completed in the same facility. In this way, the powderization process can reach nearly 100% yield as the out of spec particles can be added back into the alumina to primary aluminum process and re-atomized. As a result, the alumina, primary aluminum, and powderization processes are more mass efficient.

As shown in Tables 3 and 4, the team's proposed process for aluminum powder production reduces direct CO_2 emissions by 99.3% and indirect CO_2 emissions by 96.6%. However, there are several crucial infrastructural and technological changes that need to be made in order to assume a zero-emissions transportation and energy sector by the year 2050. While the direct emissions released from the process can be eliminated through the use of new refining technologies, electricity consumption releases a large amount of indirect emissions, especially in the alumina and primary aluminum production phases.

Table 3: Current Aluminum Production Output, Energy Consumption, and Emissions.

Conversion Step	Mass In → Out	Energy Consumption (MJ/kg)	Direct CO_2 Emissions (kg CO_2 / kg –)	Indirect CO_2 Emissions (kg CO_2 / kg –)
RM	–	0.22[27]	0.02[15]	0.03[15]
RM → Alumina	5.10 → 1.93[14]	13.57[14]	0[14]	3.2[15]
Alumina → PA	1.93 → 1.00[14]	24.60[14]	1.52[14]	11.28[15]
PA → Powderization	1.00 → 0.50[45]	0.40[Appendix C]	0[45]	0.02[76],[77]
Transportation	–	–	0.70[15]	–
TOTAL	1.00 → 0.10	38.79	2.24	11.65

Note: RM = raw material, PA = primary aluminum.

As seen in Table 3, indirect emissions associated with the electrolysis process are significantly higher than the rest of the process emissions combined, as indirect CO_2 emissions from energy production accounts for 88% of the process and will need to be addressed to create a close-to-zero carbon supply chain [16]. In order to address these issues, it is important to review the long term strategies for decarbonization of the energy sector submitted to the United Nations in accordance with the Paris Agreement. Focusing specifically on the United States Decarbonization Plan submitted in 2021, there are several zero-carbon goals set out for electricity production and transportation. The United States set a goal to reach an electricity system 100% free of carbon pollution by 2035, which will be achieved through investments in solar, wind, nuclear, and battery technologies. With this new electricity system, indirect energy emissions can be significantly reduced, as shown in Table 4. To assume the elimination of transportation emissions in Table 4, the same plan is referred to, as the United States seeks to invest in the development of low-to-zero-carbon fuels for long-distance freight shipping along with electrifying ground transportation [18]. While this submission is solely focused on the United States, there are 57 other submissions from countries around the world, showing a unified effort to reduce carbon emissions in all sectors by the year 2050 [19].

Table 4: Proposed Aluminum Production Output, Energy Consumption, and Emissions.

Conversion Step	**Mass In → Out**	**Energy Consumption (MJ/kg)**	**Direct CO_2 Emissions (kg CO_2 / kg –)**	**Indirect CO_2 Emissions (kg CO_2 / kg –)**
RM	–	0.22[15]	0.02[15]	0[15]
RM → Alumina	4.99 → 1.89[14]	13.57[14]	0[14]	0.2[15]
Alumina → PA	1.89 → 1.00[14]	32.50[14]	0[14]	0.2[15]
PA → Powderization	1.00 → 0.99	0.40 [Appendix C]	0[45]	0[76],[77]
Transportation	–	–	0	–
TOTAL	1.00 → 0.20 (100% increase)	46.68 (20.4% increase)	0.02 (99.3% decrease)	0.4 (96.6% decrease)
TOTAL (FROM RECYCLED)	1.00 → 0.52 (520% increase)	32.90 (15.2% decrease)	0 (100% decrease)	–

Note: RM = raw material, PA = primary aluminum.

5. Engine Analysis

In addition to purely energy-related considerations, it is important to understand how using aluminum will impact current engines in order to qualify the feasibility of this concept. In studies such as Pradhap *et al.* [28] and Mandilas *et al.* [29], there have been successful attempts to design an aluminum-powered, air-ingesting motor. While there was no complete engine built for the analysis, the concept has been modeled successfully. To provide a general overview of our proposed process, the aluminum powder fuel is stored as a pure product and burns via the air ingested by the jet engine. Thus, the pure Al powder will primarily react with the oxygen and nitrogen in the air to form Al_2O_3 and, in extremely small amounts, AlN as it combusts [20]. These two byproducts need to be captured before the expanding air in the combustion chamber enters the turbine. Although, this does mean that there is added complexity to the engine, and flight calculations will no longer allow for a constant decrease in plane mass as fuel is burned off, but rather an increased mass due to the higher mass of Al_2O_3 over pure Al, the advantage of complete Al_2O_3 recyclability is still much desirable.

To help ease the transition from Jet A to aluminum powder, it is important to understand what changes will need to be made to accommodate this new fuel source. The team's design strategy aimed to maintain the existing gas turbine engine components as much as possible, while minimizing necessary alterations. As shown in Fig. 2, current gas turbine engines will need to be modified to allow the combustion of aluminum powder. The fuel injection system, ignition method, combustor, and high-pressure turbine are all current components that will require some change. While the particle separator is a component that is currently being used in select engines, it has only been used in the diffuser rather than after the combustor [49]. However, the team’s proposed modifications allow for several sections of the conventional gas turbine engine to remain the same, such as the diffuser, compressor, low-pressure turbine, and exhaust nozzle. The following analysis will focus on each system which requires a modification, listing out several potential solutions for each system and grading them based on a Technology Readiness Level (TRL) to evaluate feasibility (see Appendix H).

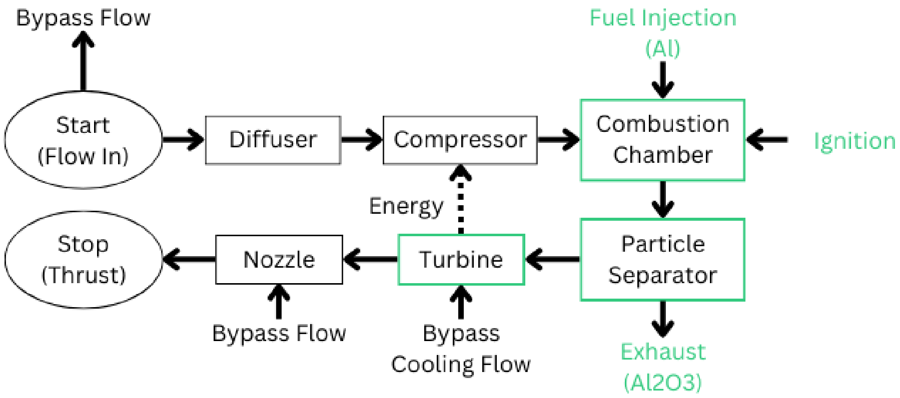


Figure 2: Modified gas turbine engine process map (green indicates changes relative to current designs).

5.1. Fuel Injection

Transitioning from liquid to solid fuel, engine suppliers will need to consider changes to the fuel pump and injection nozzle, as the aluminum particles can abrasively damage these components and will not spread into a fine mist through the injection nozzle [51]. For micro-sized and nano-sized aluminum particles, agglomeration of the particles is also a major concern. If particles clump together, the specific surface area of the agglomerated large particle is decreased, which in turn lowers the reactivity of the metal and decreases combustion performance [11]. While current injection nozzles allow liquid fuel to be atomized into a fine mist capable of producing a uniform combustion profile, a similar system of dispersing solid particles will need to be implemented for proper aluminum powder combustion [50].

Commercially available methods of dispersing metal powders do currently exist and are used in laboratory settings. These solid fuel injection systems involve a Venturi tube wherein high-velocity air flow creates a low-pressure zone capable of sucking powder from a holding chamber into the high-velocity air flow, mixing it. This mixture of air and powder creates an aluminum powder aerosol that advantageously sends a homogenous mixture of air and fuel into the combustion chamber, helping to reduce the agglomeration of particles [52]. Because of this system's wide use in commercial and laboratory applications, our team believes that engineers can easily convert it, using readily-available high-speed air during flight to properly inject our fuel and implement effective mass-flow and air-fuel ratio controls. Studies have demonstrated the benefits that premixing fuel and air has on NO_x emissions reduction [53], but these studies are primarily focused on current jet fuels. The team expects the engine body geometry to be slightly altered to accommodate this new fuel injection system, and the additional air flow needed for this system may result in slight pressure drops in the core bypass flow, but we believe all modifications will fit within the parameters of pre-designed nacells. Overall, the team believes that this method of fuel injection is feasible but will require further research and development, categorizing this solution as TRL 4 [54].

5.2. Fuel Ignition

Ignition systems in modern aircraft engines must be capable of supplying sufficient ignition energy, establishing a flame throughout the combustor, and relighting in the case of combustor flame-out. Due to the low ignition temperature of Jet A, aircraft engines make use of spark plugs to generate a spark capable of igniting the fuel-air mixture and fulfill the previously mentioned ignition system requirements [50]. However, the use of aluminum powder requires using an ignition source capable of producing much higher temperatures because the combustion reaction of aluminum can only begin once the aluminum oxide layer is melted, exposing the inner aluminum to air and beginning the autoignition process [55]. This ignition temperature is also dependent on the particle size, as combustion studies have shown that ignition temperature decreases with decreasing particle size, ranging from 3770 °F at a particle diameter of 10 μm to 1219 °F at a particle diameter of 100 nm [55].

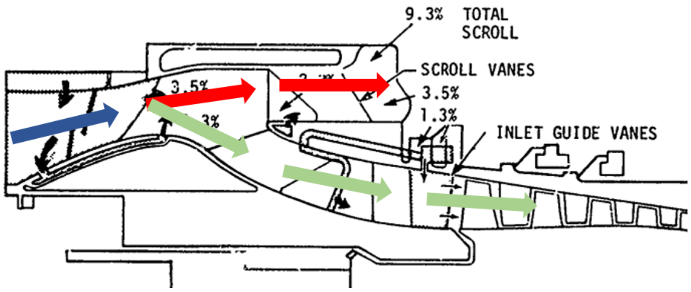
The appeal of an elegant, high-energy igniter capable of producing ignition in unfavorable aerodynamic conditions has been the inspiration of multiple solutions that the team believes can be used to reach the higher ignition temperatures required for aluminum powder. During several laboratory experiments of metal powder combustion, an oxyacetylene torch was used to begin the high temperature initial reaction [52]. Outside of the laboratory, patents for torch igniter designs in commercial aircraft engines have been filed and exchanged by large aerospace companies, such as Aerojet Rocketdyne, Pratt & Whitney, and Boeing [57]. Experimentation of a liquid and gaseous methane/oxygen torch igniter for rocket propulsion systems has been extensively studied and produces flame temperatures over 4940 °F [58]. Engineers must consider the type of oxidizer and fuels used and ensure that their byproducts would not interfere with the aluminum-air mixture in the combustor. Another high energy igniter currently being experimented with in aircraft engines are plasma igniters. Plasma jet ignition devices produce high-velocity, high-temperature flame kernels capable of traveling through the fuel-air mixture and demonstrate better performance characteristics than conventional spark plug ignition systems [56]. The team expects slight combustion chamber modifications to fit the new ignition system housing and the additional fuel/oxidizer storage and control components. This solution can be categorized as TRL 6 for both ignition methods due to the extensive research and recent prototype testing. For smaller size aluminum particles, less intensive ignition methods are required due to the lower ignition temperature of around 1219 °F, meaning that more conventional ignition systems can be retained or slightly modified. With this smaller particle size, the ignition system can be categorized as TRL 8, which can further be raised after use in a successful mission [59].

5.3. Combustion Chamber

For the combustion chamber, factors such as the fuel adiabatic flame temperature, cooling methods, and material selection all need to be considered when determining the most efficient combustor design. The adiabatic flame temperature of Jet A fuel and aluminum when combusted in air is about 3680 °F and 5923 °F, respectively [55], [60]. One viable method to bring flame temperatures down and minimize the needed combustion chamber modifications is to use a smaller particle size. Several laboratory experiments have shown that using micro-sized aluminum particles or larger produce flame temperatures of around 5431 to 6380 °F when combusted in air at 1 atm. These experiments tested the same sized particles while varying pressure and oxygen percentage, showing higher flame temperatures with increasing ambient pressure and oxygen percentage [55], [61]. Aluminum nanoparticles demonstrated much lower flame temperatures, even in higher oxygen percentage and ambient pressure conditions. The study of an 80-nm aluminum particle during combustion demonstrated that for an environment at 50% oxygen percentage and 4 atm, the flame temperature ranged from 2600 to 4220 °F, which is much lower than the previously listed flame temperatures [61]. Assuming that the turbine inlet temperature is the same as the previously listed flame temperatures, this inlet temperature can be reduced from 3680 to 2600 °F, decreasing the engine's TSFC substantially by around 10% by correlating a 100 °F decrease in inlet temperature to about a 1% decrease in TSFC [89]. While changing the particle size affects factors such as burn time, particle agglomeration, and volume fraction of Al_2O_3 to Al, engineers working on the implementation of aluminum powder can take advantage of several of the previously mentioned properties. Designing sections of the combustor to have lower or higher oxygen percentages for optimal combustion efficiency—as is commonly done today [50]—along with choosing an optimal particle size enables engineers to mimic flame temperature properties of Jet A fuel and allows for the combustor to maintain similar wall cooling flow and mixing before the hot gasses reach the turbine inlet. The team believes that the combustor can be categorized as TRL 4, as these combustion tests are validated in a laboratory environment. Further testing and research is required to fully implement this fuel source into a modified gas turbine engine, mainly focusing on testing performance characteristics of varying particle sizes. The team has also researched several new cooling methods focusing on materials selection, airflow manipulation using latticework ducts, and regenerative cooling techniques [62], [63]. By 2050 it is assumed that more effective and capable cooling methods will be available for use in gas turbine engines, however the team believes that the current most feasible way to control combustion chamber temperatures without introducing new complex materials and cycle complexity is to manipulate the particle size and chamber oxygen percentages.

5.4. Particle Separation

The particle separation system is necessary to remove and capture all of the alumina particles that are produced in the combustion chamber. There are two methods that we believe can be feasibly incorporated into an engine. The first method is attaching a particle separator that is traditionally used to remove sand and debris ingested into the engine as described in the “Integral Engine Inlet Particle Separator Design Guide” [49]. This system works by giving the particle-air mixture a centrifugal force to move the particles to the outer edges and then forcing the flow to turn. The subsonic air would be able to make the turn, but the high forward momentum and radial distance from the bend would not allow the alumina particles to make the turn, sending them into the removal ducts. In Fig. 3, the path each part of the flow would follow is shown. The data in the paper suggests that this can be at least 95% effective in capturing alumina based on the weight and particle size, which is a reasonable effectiveness. Alumina has a density over double that of typical sand used in the paper and would have over twice the momentum for a particle of the same size as a result, leading to an even higher expected efficiency [70], [71]. The main problems with this concept are the necessary incorporation of swirl and de-swirl vanes immediately after the combustor. This would lower the efficiency of the turbine as the flow would be interrupted before it reaches the blades. Additionally, the blades will be subjected to the extremely high temperature of the flow as it exits the combustor. Furthermore, the swirl vane would have erosion issues and need constant surveillance and maintenance to ensure no major issues occur. While all of these issues may have solutions, the team does not have the means to properly explore and qualify them, as physical testing would be necessary to determine all the details of separating high-temperature, high-momentum alumina particles. The team is confident in categorizing this method as TRL 6 as particle separation technology has been tested and implemented in jet engines for decades. The only obstacles to overcome technologically are core geometry changes and component temperature resilience. Both issues are not unique to this system, and we believe this would qualify as having a fully-functional prototype.



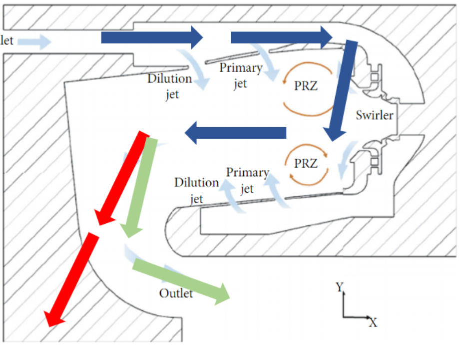


Figure 3 (Left): Particle separator diagram [49].
Figure 4 (Right): Reverse flow combustor diagram [72]. Blue arrows show the path of alumina-air mixture, red arrows show the path of the separated alumina, and green arrows show the path of clean air.

The second method of particle separation the team identified is a modification to the combustor, primarily its geometry. A standard combustor may be modified into a reverse-flow combustor and achieve the same particle filtration effect as described earlier using the centrifugal method, with only slight modifications. While reverse-flow combustors are typically used in smaller engines, they have the potential to be useful here as well [72]. By utilizing the “S”-shaped turn and taking advantage of the flow’s swirl, it may be possible to separate the alumina particles from the air flow using the same momentum-based principle as in the first method. This can be better seen in Fig. 4, which shows the proposed particle paths in a generalized reverse-flow combustion chamber diagram. The team is confident in assigning TRL 2 as there is currently no publicly-accessible research on particle capturing technology inside of a reverse-flow combustor and our analysis is highly speculative. For either method, a pressure gradient would need to be established to ensure all particles enter the holding chamber with some type of added check valve to eliminate the possibility of the particles reentering the core flow and being discharged out of the nozzle into the atmosphere. Both also create significant geometric changes, which may have an impact on the high pressure turbine design. While this is uncertain, it is something worth considering.

5.5. NO_x Emissions

The combustion of aluminum in an ambient air environment produces trace amounts of nitrogen oxide (NO_x). NO_x emissions are known toxins; provisions to lower their emissions or mitigate their effects are necessary. There are two paths to lowering emissions: (1) reduce the quantity of NO_x particulates generated in the combustion process or (2) remove generated NO_x particulates from the exhaust flow.

Current research into metal powder combustion has shown that in the case of magnesium (Mg) powder combustion in air—an energetically similar combustion process to Al in air—NO_x emissions remain equal to or lower than emissions from gasoline-based combustion processes [73]. In the worst case, NO_x emissions will remain equal in quantity to current emissions. However, emissions generation can be reduced by controlling the aluminum combustion temperatures and the air-fuel ratio. A well known method called exhaust gas recirculation (EGR) may be used to lower the temperature in the combustion chamber by returning some of the exhaust gas back into the combustor inlet, thus acting as a diluent to the main air stream entering the combustion chamber. A greater volume of air increases the aluminum particle burn rate, which in turn decreases overall combustion temperature [74]. Decreasing combustion temperatures has been shown to significantly reduce NO_x formation [73]. Although EGR creates more losses in the exhaust, it may be necessary to reduce NO_x emissions. Any temperature decrease must also be balanced with the decrease in combustion efficiency that lower temperatures yield. Nevertheless, EGR is an already widely used technology that could be readily implemented into a turbofan engine, so the team evaluates this technology as TRL 8.

The second method is to simply remove any solid NO_x particulates from the exhaust stream using the existing aluminum particle separation system. According to the EPA, the smallest particles that “have shown toxicity have a diameter of about 3% to 5% of the wavelength of any color of visible light” [75], which translates to a minimum particle size of 11.4 nm. The existing alumina particle separator would be able to filter these small NO_x particles, but with a lower capture rate due to the smaller particle size. This system would advantageously require no additional modifications to the engine alongside those needed for the alumina particle separator. Overall, Appendix I outlines each engine component along with the proposed changes, features, challenges, and assigned TRL levels to highlight the main areas of interest for engine modifications.

6. Production Rate Analysis (Present–2050)

Appendix E shows that 100 million MT_{Al} is needed to produce enough fuel for the United States’ current commercial aviation industry. It is also estimated that 80% more aluminum is needed for other industries. Fortunately, the extra 100 million MT_{Al} is not per year but merely a one-time starting number due to the proposed recycling methods. As long as that amount can be saved by 2050, much less new aluminum will need to be added. During the aluminum combustion, the only substantial byproduct is Al_2O_3, with AlN being created only in trace amounts [30]. For the purpose of this analysis, we have assumed that “trace amounts” means less than 5%. This means only 5 million MT_{Al} would need to be added per year, with the rest being recycled.

This works out to be an average production rate of 127 million MT_{Al} per year by 2050, as long as 100 million MT_{Al} is saved between 2023 and 2050. Fig. 5 shows the total amount of aluminum we propose needs to be produced compared to what would only meet predicted market demands. The deviation in the plot is extremely small. Fig. 6 shows the rate of aluminum production per year. We propose a greater increase in production in the middle years as it will be easier to increase the rate of production and renormalize it to what is only needed to meet other consumer demand and non-recycled aluminum. Fig. 7 shows this process as well, as seen by the curve in the rate of change increasing initially, and then decreasing lower than would be needed for only consumer demand. This allows for a smaller ratio of rate of change to rate of production, which is an easier goal to reach. The main point is that 127 million MT_{Al} will need to be produced per year in 2050 with an additional 100 million MT_{Al} stored for use as fuel in order to meet consumer demand exclusively. Separate facilities will need to be created to handle alumina recycling beyond 2050, the cost of which is analyzed in an upcoming section.

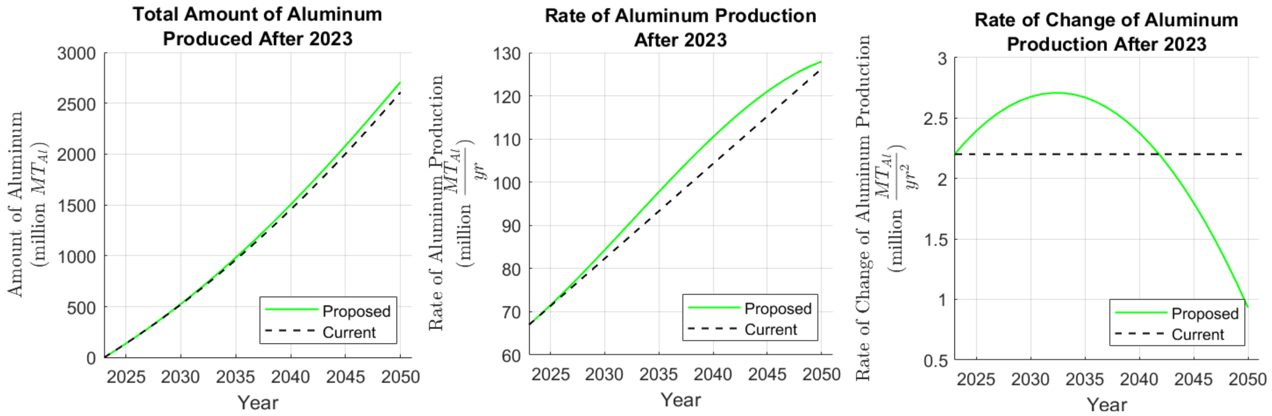
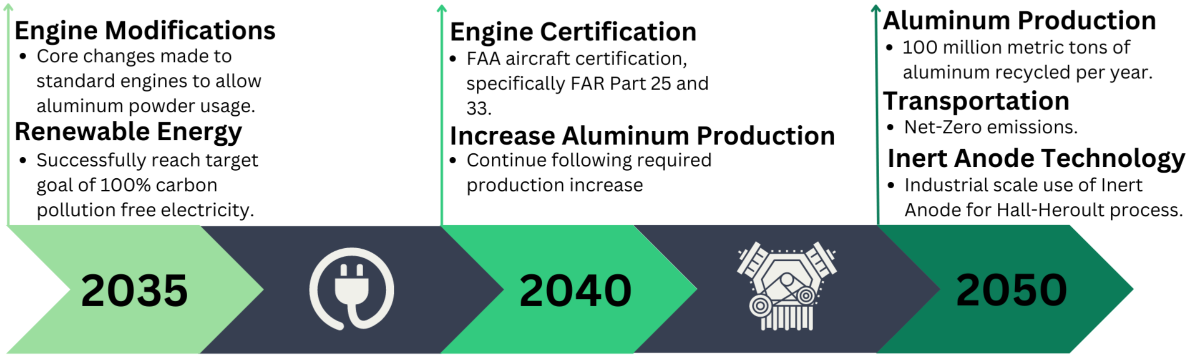


Figure 5 (Left): Projected total amount of aluminum produced after 2023 for each year.
Figure 6 (Middle): Projected rate of aluminum production after 2023 for each year.
Figure 7 (Right): Projected rate of change of aluminum production after 2023 for each year.

7. Timeline

The timeline presented in Fig. 8 is a culmination of technological and infrastructure advancements that need to be made leading up to 2050 in order for the source-to-flight lifecycle of aluminum powder to be very close to net-zero carbon emissions. Renewable energy and net-zero emissions from other modes of transportation are pivotal for the mitigation of carbon emissions throughout the team's proposed process. Industrial-scale use of the inert anode technology required in the primary aluminum production phase will eliminate the majority of direct CO_2 emissions from the process.



Engine Modifications
- Core changes made to standard engines to allow aluminum powder usage.

Renewable Energy
- Successfully reach target goal of 100% carbon pollution free electricity.

Engine Certification
- FAA aircraft certification, specifically FAR Part 25 and 33.

Increase Aluminum Production
- Continue following required production increase

Aluminum Production
- 100 million metric tons of aluminum recycled per year.

Transportation
- Net-Zero emissions.

Inert Anode Technology
- Industrial scale use of Inert Anode for Hall-Heroult process.

Figure 8: Timeline of technological advancements, infrastructural changes, and production milestones.

Ensuring that modified aircraft and engines are FAA certified within a reasonable timeframe is necessary to justify that these new aluminum-powered aircraft will be ready for commercial use by 2050. The team believes that the two most important and applicable sections of the FAA aircraft certification process are FAR Part 25 and 33, which stipulate the requirements for aircraft and engine readiness, respectively [82], [83]. To determine a reasonable timeline for these certifications, the certification of the Boeing 737 MAX is used as reference. For minor changes, the FAA issues an amended type certificate, which typically takes 3 to 5 years to complete. For comparison, the certification of a new aircraft type can take between 5 to 9 years [84]. As such, the team believes the certification of this new aircraft type will take approximately 9 years, and should be started no later than 2035 once engine modifications are finalized. Fuel procurement may also need to be addressed, as some of the largest alumina manufacturers are based in China, Russia, India, and Brazil [41]. If aluminum powder fuel becomes a viable energy source for the entire aviation industry, it is possible that the price and availability of aluminum from those countries may fluctuate significantly. However, this has been neglected for the following cost analysis.

8. Cost Analysis

A cost for implementation of the supply chain can be estimated by adding up the most significant upfront and recurring costs. Upfront costs include the costs to build new aluminum plants, source the aluminum, conduct new engine research, and retrofit aircraft with the modified engines. The dominant recurring cost is the cost of electricity (included in the cost of fuel). Other recurring costs are set by the cost of smelter maintenance (i.e., cost to replace anode and cathode of the electrolytic cells, also in the cost of fuel), engine maintenance, labor, and transportation. The estimated upfront and recurring costs are $785 billion and $178 billion per year, respectively. Table 5 summarizes all the aforementioned costs. See Appendix B for more details on how each estimate was determined. In order to reach a point of profitability, further extreme cost-reducing factors must be explored. This can be achieved through energy contracts, government subsidies, or decreases in raw material costs for smelter equipment.

Table 5: Cost Summary.

Upfront		**Recurring**		**Jet A**
Source	**Cost**	**Source**	**Cost per Year**	**Cost per Year**
Smelter Facilities	$230B	Cost of Fuel	(From Recycling) $102B	30B
Retrofit Planes	$319B	Engine Maintenance	$40B	40B
Original Aluminum	$236B	Cost of Labor and Transportation	$36B	17.5B
Researching New Engine	$25M			
TOTAL	$785B	**TOTAL**	$178B (103% Increase)	$87.5B

9. Conclusion

Overall, the team has demonstrated the potential that aluminum powder has to supersede the use of Jet A in the aviation industry. With a 96% reduction in emissions, minimal changes to the current aluminum production chain, and comparable propulsive capabilities to Jet A with additional benefits, aluminum powder is capable of becoming a mainstream alternative aviation energy source. To further validate the feasibility of this alternative fuel source, the team has presented a modified gas turbine engine capable of handling the combustion and filtering of solid fuel while addressing the main difficulties associated with burning aluminum powder. The cost summary demonstrates that the total upfront and recurring costs associated with transitioning and using this new fuel source is significantly larger than the costs associated with using Jet A fuel. However, steps in the future can be taken to improve the recurring costs by reducing the smelter operating costs and utilizing cheaper renewable energy. Being able to retrofit current airplanes with modifications to handle aluminum powder combustion, significantly reduce harmful emissions, and minimally change the current supply chain are all areas where the team believes this solution will truly stand out, making it the best potential candidate as the clean aviation energy source of the 2050s and beyond.

APPENDICES

Appendix A: Weight Calculations

Since aluminum powder has a specific energy 30% less than that of Jet A, an aircraft would need to carry a larger mass quantity of aluminum powder than it would of Jet A to provide it with the same energy. This difference in mass can be estimated by approximating the energy of a given quantity of Jet A and then solving for the amount of aluminum powder with the same corresponding energy. For reference, a Boeing 747 has a fuel burn rate β [46], [47] of

$$\beta = 4 \text{ liters per second}$$

or

$$\beta = \left(\frac{4\,L}{1\,s}\right) \times \left(\frac{3600\,s}{1\,hr}\right) = 14{,}400 \text{ liters per hour}$$

which is roughly

$$\beta \approx 15{,}000 \text{ liters per hour}$$

Assume the density ϱ of Jet A is 800 kg/m^3 [48]. During a flight duration T of 2 hours, the Boeing 747 burns a fuel mass m_{JetA} of approximately

$$\mathrm{m} = \mathrm{T}\beta\varrho$$

$$m_{JetA,\,2hr} = (2\,hr) \times \left[\left(15,000\,\frac{L}{hr}\right) \times \left(\frac{0.001\,m^3}{1\,L}\right)\right] \times \left(800\,\frac{kg}{m^3}\right)$$

$$m_{JetA,\,2hr} = 24,000\,kilograms$$

The equivalent energy E for a 2-hour flight's worth of Jet A is

$$E_{2hr} = m_{JetA,\,2hr}\,e_{JetA}$$

where e_{JetA} is the effective specific energy of Jet A. The energy is approximately

$$E_{2hr} = (24,000\,kg) \times \left(16.1\,\frac{MJ}{kg}\right)$$

$$E_{2hr} \approx 387,000\,megajoules$$

The mass of aluminum m_{Al} corresponding to the same amount of energy of a 2-hour flight's worth of fuel is

$$m_{Al,\,2hr} = \frac{E_{2hr}}{e_{Al}} = \frac{387{,}000\,MJ}{14.4\,MJ/kg}$$

$$m_{Al,\,2hr} = 26,875\ kilograms$$

The difference in mass Δm is

$$\Delta m_{2hr} = m_{Al,\,2hr} - m_{JetA,\,2hr}$$

$$\Delta m_{2hr} = (26,875\ kg) - (24,000\ kg)$$

$$\Delta m_{2hr} = 2875\ kilograms$$

This means 2875 kilograms more aluminum is needed than kilograms of Jet A to provide a Boeing 747 with the energy required for a 2-hour flight.

Appendix B: Cost Calculations

Cost Due to Smelters

- Current smelters run with an idle capacity of approximately 30% [64]
- We need 223 million metric tonnes of alumina → aluminum per yr in 2050 for consumer market and to use as fuel (see Appendix E).
- 1000 metric tonnes per unit per year [65]
- This means we need 223,000 units total
- We are producing 70 million MT/yr with 30% idle capacity [17]

$$\frac{70{,}000\ units}{output_{current,\,max}} = \frac{100\%-30\%}{100\%}$$

$$output_{current,\,max} = 100,000\ units$$

  - 70,000 in use, 30,000 idle
- Additional (new) units needed are

$$output_{additional} = output_{needed} - output_{current,\,max} = 123,000\ units$$

- Assume industry will take care of all aluminum from mining as it always has
- Need to process only 95 million metric tonnes per year (from recycled)
- This means we need 95,000 units
- 65,000 new units needed after incorporation of idle units
- Assume 300 units per plant = 300,000 metric tonnes per year
- 215 plants needed
- Cost of facility to do 600,000 MT/yr is $2.3 billion (RUSAL) [66]
- This goes to

$$\frac{65\ million\ MT/\,yr}{0.6\ million\ MT/yr} = \frac{x}{\$2.3\ billion}$$

$$x = \$250\ billion$$

- Energy per kg of Al is 13.88 kWh/kg Al which accounts for electrolysis energy and anode/cathode manufacturing energy [14]

- Total energy is

$$total\ energy\ =\ (13.88\ \frac{kWh}{kg\ Al})\ \times\ (95\ \times\ 10^{9}\ \frac{kg}{yr}\ Al)\ =\ 1.32\ \times\ 10^{12}\ \frac{kWh}{yr}$$

- Assuming cost of energy is ~10 cents/kWh, total yearly cost is

$$total\ yearly\ cost\ =\ (1.32\ \times\ 10^{12}\ \frac{kWh}{yr})\ \times\ (\frac{10\ cents}{1\ kWh})\ \times\ (\frac{\$1}{100\ cents})\ =\ \$137\ billion/yr$$

- TOTALS:
  - **Upfront: Facility Construction Cost is $250 billion**
  - **Recurring: Electricity/Anode Replacement is $137 billion/yr**
- Cost reduction suggestions
  - Find cheap land (minor difference as land is cheap compared to everything else)
  - Restart closed (not idle- idle accounted for above) facilities
    - Assume they can produce 5-10 million MT/yr
    - Leads to upfront cost reduction of ~$20 billion
  - Use high efficiency solar/hydroelectric power to reduce energy costs
    - Electricity cost from solar is ~ 7 cents/kWh [67]
      - Leads to recurring cost reduction of ~$45 billion/yr
    - Electricity from hydroelectric ~8.5 cents/kWh [68]
      - Leads to recurring cost reduction of ~$25 billion/yr
    - Using combo could save ~$35 billion per year
- ***Cost reducing energy contracts may be available
- TOTALS AFTER COST REDUCTION SUGGESTIONS:
  - **Upfront: Facility Construction Cost is $230 billion**
  - **Recurring: Electricity/Anode Replacement is $102 billion/yr**

Cost of Replacing/Retrofitting U.S. Air Fleet

- 5800 planes total in U.S. fleet [78]
- $110 million per plane [79]

$$5800\ planes\ \ *\ \ \$110\ per\ plane\ \ =\ \ \$638\ billion$$

- Assume 50% cost reduction if the current fleet can be retrofitted to handle the new fuel

$$\$638\ billion\ *\ 50\%\ \ =\ \ \$319\ billion$$

Cost of Original Aluminum

- Aluminum cost is $2355/MT [80]
- We need 100 million MT to start.
- Total cost is

$$\$2355/MT\ \ *\ \ 100\ million\ MT\ \ =\ \ \$236\ billion$$

Cost of Engine Research

- Cost of engine research is $25 million [81]

Cost of Engine Maintenance

- $40 billion/yr [86]

Cost of Labor and Transportation

- Assume labor adds 5%
- Assume transportation adds 20% [85]

COMPLETE COST TOTALS

- Upfront

$$\$230\, billion\ +\ \$638\, billion\ +\ \$236\, billion\ +\ \$25\, million\ =\ \$1.1\, trillion$$

- Recurring

$$(\$102\, billion/yr\ +\ \$40\, billion/yr)\ \times\ 1.25\ =\ \$178\, billion/yr$$

Cost of Jet A

- Cost of Jet A per MT is

$$(\$756/MT)\ \times\ (48\, million\ MT/yr)\ =\ \$36.3\, billion/yr$$ [69]

- Add Engine Maintenance of $40 billion/yr
- Total cost is $76.3 billion/yr

Appendix C: Energy Calculations

- Standard atomization process runs at roughly 15 MPa [42] or 2000 psi, which is similar to a standard pressure washer [42].
- It is known that a standard pressure washer uses approx 1500 kW/hr to produce 2000 psi of water pressure [43].
- 1500 kW/hr is equivalent to 0.5 kJ.
- Standard atomization processes run through ~3000 kg/hr [42] of aluminum [42].
- To create an aluminum melt pool, it takes 390 kJ/kg of Al [42] once the aluminum has first been melted. We assume the process is mature and in high volume, so startup energy cost is ignored [44].
- So,

$$0.005\ \frac{MJ}{kg} + 0.390\frac{MJ}{kg} = 0.395\ \frac{MJ}{kg}\ Al$$

Appendix D: Average Flight Time Calculation

- Using data from tables lets us calculate the average time of a flight for U.S. airlines. Using data from 2020,

$$\frac{Total\ Flight\ Hours\ (for\ the\ year,\ 2020)}{365\ \times\ Departure\ per\ Aircraft\ per\ Day\ \times\ Total\ Operating\ Fleet}$$

  - Provides **average flight time for a plane is 2.39 hrs**

Appendix E: Total Aluminum Needed Per Year

- 3,748 airplanes in the U.S.
- Average of 2.32 flights per day per plane.
- Average flight time of 2.39 hours per flight.

$$Annual\ Demand_{Al}\ =\ 3748\, planes\ \times \frac{2.32\, flights/day}{1\, plane} \times \frac{32{,}115.6\, kg}{1\, flight} \times \frac{365\, days}{1\, yr} \times \frac{1\, MT}{1000\, kg}$$

$$Annual\ Demand_{Al}\ =\ 101{,}928{,}696\ MT/yr$$

- 24 million MT in 2000; 68 million MT in 2021 [17].
- Expected 80% in demand by 2050 (122 million MT total)
- Need 101 million MT by 2050 saved up
- Need 5 million MT per year to replace non-recycled
- Need 127 million MT per year by 2050
- Only a 1.85 times increase compared to 2021
- There needs to be an average increase of 2.03 million MT per year

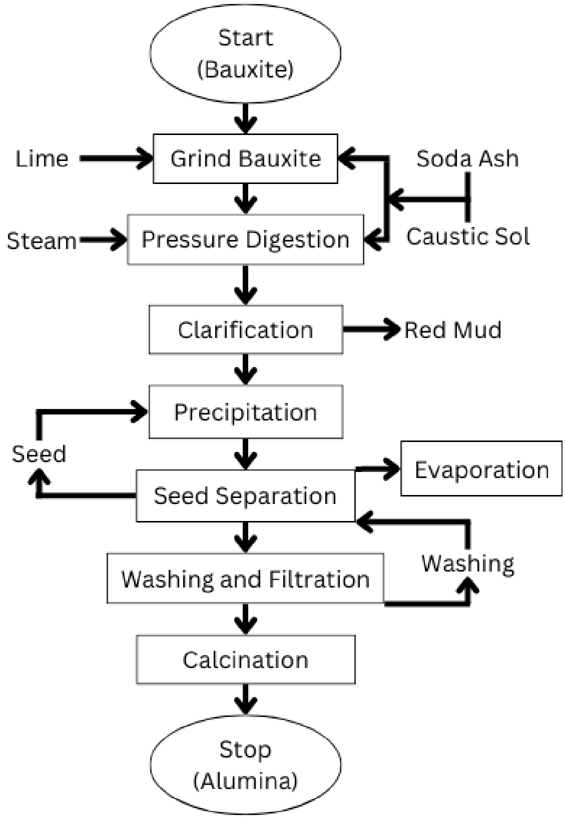
- Just under the 2.10 million increase per year on average from 2000 to 2021
- Evenly split the savings for the 101 million MT leads to 3.75 million per year

Appendix F: Emissions Comparison Calculations

- MMT: million metric tonnes
- Total CO_2 emissions = 920 MMT [6]

$$CO_2\ emissions\ from\ Al = (101\ MMT\ Al) \times (0.42\ \frac{MMT\ CO_2}{MMT\ Al})$$
$$= 42\ MMT\ CO_2$$

Appendix G: Bayer Process & Atomization Process Maps



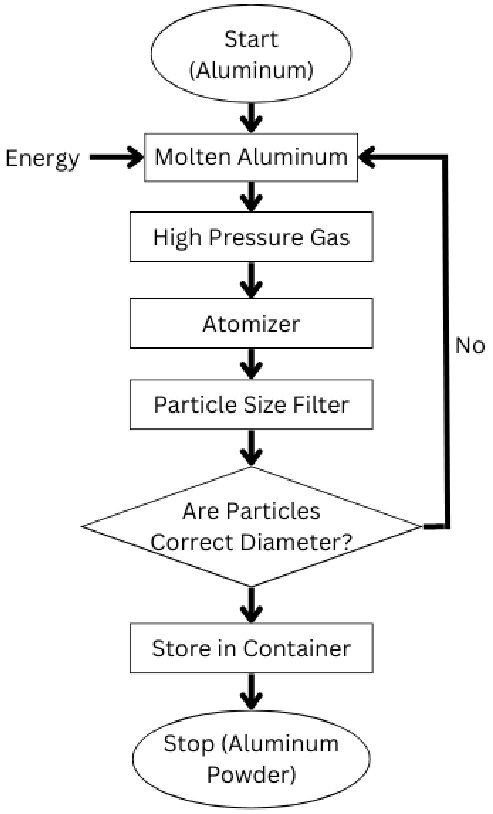


Figure G.1: Process map for bauxite to alumina.

Figure G.2: Process map for aluminum atomization.

Appendix H: NASA TRL Stages

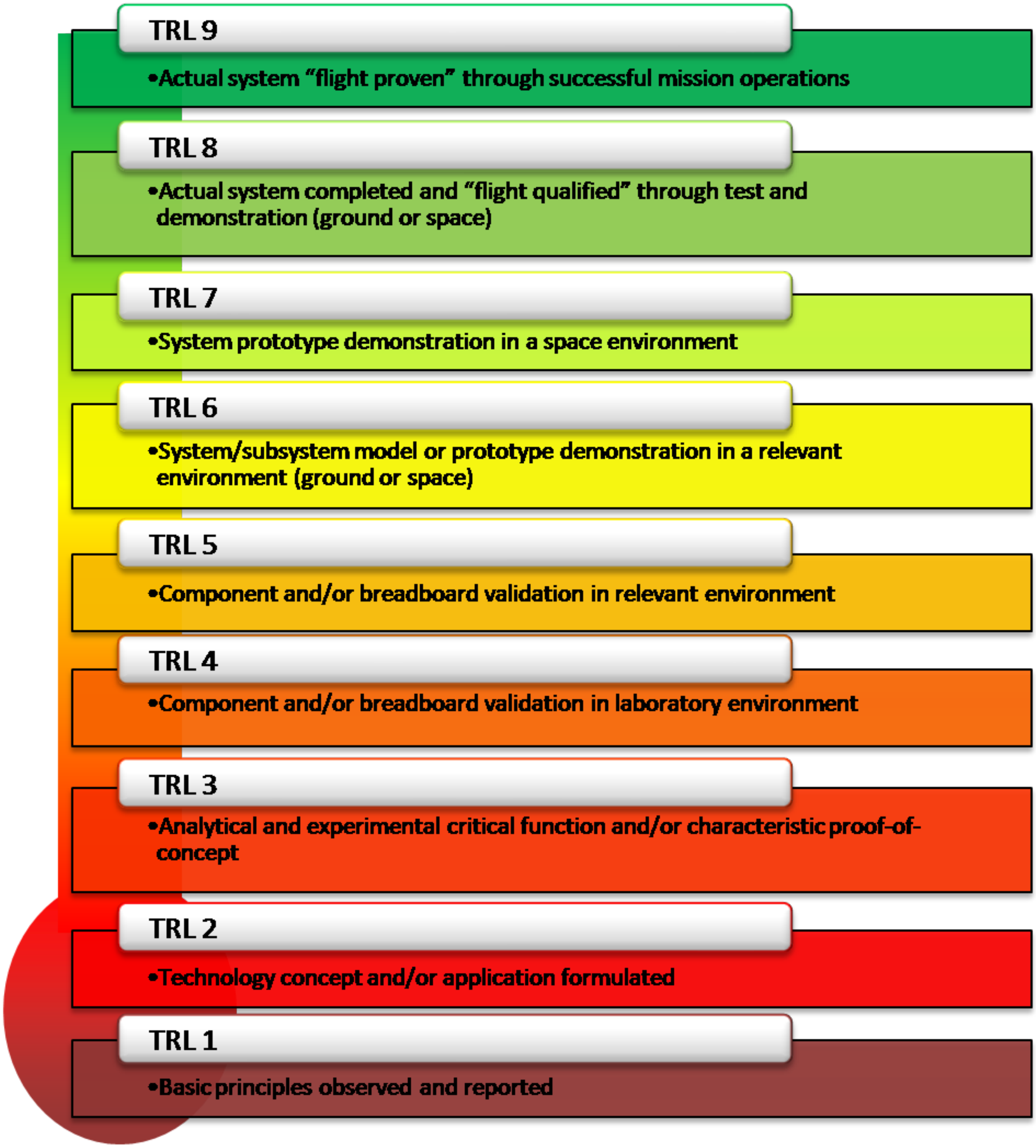


Figure H.1: TRL levels taken from NASA website [54].

Appendix I: Engine Analysis Summary Table

Table I.1: Engine Analysis Summary.

Component	Changes	Features	Challenges	TRL
Inlet	–	–	–	–
Compressor	–	–	–	–
Combustor	Fuel injection	Disperses solid-air mixture in combustor	Aluminum fuel storage	4
			High speed air required	
	Plasma igniter	Melts oxide layer to begin auto-ignition	Higher ignition temp	6
	Spark plug	Melts oxide layer to begin auto-ignition	Physical testing required	8
	Reverse flow	Separates particles in combustor	Increased surface area to cool	2
			Storing alumina	
Particle Separator	New component (if not using reverse flow combustor)	Separates particles after combustion	Recouping scavenged flow	6
			Storing alumina	
High-Pressure Turbine	New materials	–	Material temperature limits are nearing maximums	–
Low-Pressure Turbine	–	–	–	–
Exhaust	–	–	–	–

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