Team 9: World’s Strongest CAN
Process of ALON Production

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Engr340 Senior Design Project
Calvin College
11 May 2016
Senior Design Final Report

Calvin College
11 May 2016
Professor Jeremy Van Antwerp
Executive Summary

Aluminum oxynitride, produced via numerous chemical reactions and multiple physical manipulations, is an optically transparent ceramic that is mechanically very durable. So durable in fact, that it is being used more and more by the military, as well as other defense corporations as a lightweight substitute for bulletproof glass. This material has the potential to revolutionize defense applications. The current implementation of AlON into the commercial market is an area that is on the rise, with a plethora of benefits related to further integration of this product into the market. The applications for this product are vast, however the price at which it is available is significantly higher than alternatives, with a price tag more than 250% higher than traditional transparent ceramic equivalents.

The goal of this project is to design a process capable of transforming aluminum used beverage cans (UBCs) into 450 tons of AlON in powder form per year. The decision for the outcome of this project is to market this powder to various companies who will be able to create the transparent ceramic AlON via hot isostatic pressing. The feedstock for this process will be, as mentioned above, recycled aluminum beverage cans, which will recycled at the beginning of the process to acquire pure aluminum which can be transformed into AlON powder.
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1 Introduction

1.1 Course Introduction

Calvin College Engineering Program uses a senior capstone project as the culmination of learning throughout the past four years. This project includes two separate courses: ENGR 339 and ENGR 340 combining for a total of six credit hours, both of which are required for graduation. The fall semester course, ENGR 339, focuses students’ attention towards team formation, project development and identification, and project feasibility. The spring semester course, ENGR 340, delves into the process of fulfilling the requirements of the proposed project set forth in the fall semester. Throughout both courses, Christian design norms and broader worldviews are incorporated into the curriculum through multiple lectures and mentorship. The culminating result of this project is the successful deliberate application of the technical aspects of the engineering design process, with a tangible and practical outcome.

1.2 Problem Statement

AlON ceramic is a highly utilizable material on the commercial market. With material properties such as high strength and good transmission, AlON has been found to be superior in protection to currently employed bulletproof glass. This material has the potential to revolutionize the defense industry in both military and civilian applications, giving people the ability to provide a higher level of protection. The current production of AlON is an up and coming process, currently only being produced by one company, Surmet. Due to the quasi-monopolization of this field, and the methods and raw material costs of producing AlON, the market price for the consumers is extremely high.

1.3 Project Proposal

The World’s Strongest Can design team is proposing a process to produce aluminum oxynitride through a method that is cheaper and more readily available for implementation for defense and protection corporations. To achieve the cheaper production, the aluminum used for the synthesis of AlON will be acquired through recycling of used beverage cans (UBC’s), and all process equipment will be scrupulously
analyzed to optimize the profit and further lower the cost. The initial goal for this project is to design a process for the production of aluminum oxynitride powder, which can later be physically manipulated via isostatic hot-pressing into the final product, the hard and optically transparent ceramic.

1.4 Design Norms

During this design project, 3 specific design norms will be kept in mind as guidelines for ethical focus: stewardship, caring, and trust

1.4.1 Stewardship

Stewardship will be displayed through this design since this process will use the recycling of aluminum which will reduce aluminum being wasted. This is important because preserving the scarce resources that God gave us as much as possible is an imperative component of Christian engineering.

1.4.2 Caring

Caring will be displayed through the impact that the final product will have on the consumer. The product being made in this design process has the ability to save lives, and jumpstarting the broader implementation of this product shows care for the people who would benefit from it.

1.4.3 Trust

Finally, this design team will strive to display trust throughout the project. We want the companies who purchase our intermediate powder to know with certainty that it is a quality product that will be used to create the AlON transparent ceramic.

1.5 Project Management

To effectively and efficiently accomplish the desired goals of this project, the team below focused on dividing responsibilities among team members, time management, and team communication throughout the course of the project.
1.5.1 Team Members

Brandon Pott

Brandon Pott was born and raised in Grand Rapids, Michigan. Although he has gone to school in Grand Rapids his entire life, Brandon enjoys travelling, specifically to the mountains. When Brandon is not busy studying Chemical Engineering, he enjoys playing and watching sports, especially football. Brandon also boasts about his loyalty to the University of Michigan athletic teams.

Galen Wood

Galen Wood was born in Andrews AFB Maryland, and spent his childhood moving around the country (and world) as a dependent of the United States Air Force. Galen enjoys long walks on the beach, playing ice hockey, and attending music festivals around the world. Galen is studying chemical engineering, however he plans to join the United States Army as an Air Defense Artillery Officer, and will be stationed in South Korea upon graduation in May 2016.
Zhihong Zhang

Zhihong Zhang is a senior chemical engineering student from Shanghai, China. He serves as the team web editor and is charge of the management of the team websites and researching process of recycling. He is studying to become a chemical engineer and is passionate about project analysis. After graduation, Zhihong plans to find a job working in the chemical engineering field.

1.5.2 Team Responsibilities

As a team, ongoing responsibilities throughout the year were divided among the team according to everyone’s strengths and weaknesses. In addition to ensuring that these responsibilities got accomplished, this method of dividing responsibilities allowed tasks to be accomplished in the most efficient manner. In addition to the following roles filled by each team member, all team members contributed to researching and analyzing throughout the course of the project. Constant status reports and meetings kept all members accountable in their responsibilities. Reports and presentations were conducted by all team members, dividing the work amongst ourselves evenly.

Team Webmaster:

Based on his keen knowledge of computers, writing code, and simulation software, Zhihong was appointed to the position of Team Webmaster. In addition to creating and managing the team website, Zhihong was responsible for running and troubleshooting any software which is used in this project. This includes Unisim, Polymath, or any other program used in this design project.
**Project Coordinator:**

As an active member of ROTC in the United State Army, Galen studies the art of leadership on a daily basis while conducting his officer training. This special skillset is carried over into other group work, where Galen exercises his knack for being a leader. During this design process, Galen was appointed the project coordinator. As project coordinator Galen gets a chance to utilize his leadership background, and is responsible for scheduling meetings, focusing meeting topics to align with upcoming due dates, and delegating work among the team. Galen also led the effort to create the overall project schedule.

**Quality Check Specialist:**

Having produced excellent results on past design projects, Brandon has shown an ability to understand the project goals and to make sure the team meets those goals, and meets those goals in a professional manner. As the quality check specialist Brandon is responsible for reviewing every document that is submitted, and making sure the ideas and designs developed by the team meet the goals of the project, as well as the standards set by the Calvin College Engineering Department.

**1.5.3 Time Management**

A crucial component in any successful project is time management. A design team must estimate the amount of time necessary to complete tasks and plan accordingly in order to meet project deadlines. Once the scope of this design project had been defined, a schedule was constructed allowing all progress to be tracked and evaluated. This schedule (Figure 1) includes all major milestones to be completed this semester, and the dates on which they should be done.
Creating such a schedule is critical to keeping the project on track and meeting the final deadline. This schedule was a “fluid schedule” and was often adjusted to incorporate unforeseen obstacles and challenges, as long as critical deadlines were still able to be met.

### 1.5.4 Team Communication

Much like time management, communication is imperative for design teams. Once work was divided among team members, weekly meetings were held to make sure every team member was staying on schedule and adequately performing the required tasks. Weekly meetings serve as a
time to voice any concerns as well as discuss overall project topics. In addition to the weekly meeting with just the team, a bi-weekly meeting was scheduled with Professor Jeremy Van Antwerp. This is a time when Professor Van Antwerp would offer guidance and technical advice, as well as answer any questions the team may have come across. The final method of communication was with the industrial mentor. The team was matched with Luke Martin and Bill Dykstra from Temper Inc., a local engineering firm with expertise in materials engineering. In-person meetings were held with these gentlemen once a semester to update on status reports and answer pressing questions. These meetings were in addition to yearlong communication with specific questions and advice, helping guide the team down accurate paths.

2  Project Overview

The following sections will provide a more detailed description of the scope of the project, and the details in which it will entail.

2.1  Purpose

The World’s Strongest Can design team has identified and selected the proposed project as a primary focus because we feel the protection of human life is important, and we want to do our part in adding to the safety and preservation of such life. As engineers, World’s Strongest Can’s members feel called to do provide a cheaper and more accessible bulletproof protection through the widening of the market for AlON ceramic. By conducting this project, citizens around the globe will have the ability to be better equipped against harmful and life-threatening encounters.
2.2  Background

With a military defense budget higher than any country in the world,¹ the United States military is always attempting to provide the best of the best for both offensive weapons, and defensive equipment. One such area that the military has been conducting research in is the field of transparent aluminum oxynitride as a substitute for traditional glass surfaces. With applications ranging from transparent armor for helicopters, aircraft, and ground vehicles, to domes for infrared guided missile systems, aluminum oxynitride has the capacity to revolutionize the safety components military wide. With substantially superior performance against conventional ballistics, as well as high performance against improvised explosive devises,² AlON transparent armor is a much safer alternative to its glass-based counterpart. While the benefits of the evolution from a fully glass-based armor for all military defensive equipment are vast and evident, the downside to this transformation is its cost. The current production of currently implemented glass based armor ranges around $4 per square inch, where an equivalent slab of aluminum oxynitride armor would be upwards of $10 per square inch.³ With such a higher price, AlON has not yet been able to penetrate its way fully into the military just yet.

In addition to the military market, bullet proof protection is a high commodity in commercial applications as well, including home defense or business defense. Examples of civilian applications include armored truck companies, banks, hospitals, and many other areas where protection and safety is of an utmost importance.

AlON ceramic is a new technology, without much widespread knowledge of its capabilities.

Currently only being produced by one company, Massachusetts based Surmet corporation, the availability of this product is limited, and as previously mentioned, the costs are extremely high.

2.3 Project Scope

The initial scope of this project included determining the feasibility of this project and design. The feasibility study performed included the analysis of the data discovered during research, and the design alternative phases. The feasibility study laid the framework for what steps would need to be accomplished throughout the project. With the goal of producing a process to create broader widespread commercialization of AlON, the feasibility study set the limits for where World’s Strongest Can’s design team would end their production process. As seen in the rough schematic below, AlON ceramic is created via the hot-pressing of the AlON powder.

![Figure 2- AlON ceramic production route](image)

The analysis of self-production of AlON ceramic versus marketing the powder was a large portion of the feasibility study performed in the first semester of the project, as the implications of this decision held a significant weight on the scope of the project as a whole. Upon research into the hot pressing process, it was determined that the scope of this design process would terminate at the synthesis of the AlON powder. The addition of designing the hot pressing process would almost double the workload for designing, and realistically, would create a plant so varied in function that it would not be economical to run. Therefore it was deemed unfeasible to design the process all the way to ceramic production. The focus for the commercialization of the AlON ceramic then shifted from the sale of the ceramic to the market directly, to the sale of the powder to companies with isostatic hot-pressing capabilities, to then be sold to the market. This then opens a new niche in the commercial market as AlON powder suppliers, enabling other companies to enter into the existing market of AlON ceramic sale with price tags significantly lower than
those in the current market.

Once this scope was set in stone, the deliverables for this project then were established. These deliverables include a complete plant design for the AlON powder production, from raw material to finished product. This design includes an all-inclusive equipment list with optimized operating conditions and equipment sizing. All optimized design parameters will be backed up with an economic analysis of the individual decisions, as well as the plant as a whole. Additionally, this project will include a Process Flow Diagram of the process, and finally a business plan and market analysis for commercialization of the process.

2.4 Project Constraints

The only constraint for this project was that the original raw material aluminum that will be used in the AlON synthesis must be acquired from the recycling of the used beverage cans. In the team’s attempt to lower production costs, and therefore selling costs of the AlON powder, the integration of recycling methods was a huge stepping stone. With this constraint in mind, the rest of the optimization decisions are free from constraints or limitations.

2.5 Approach

This section highlights the steps taken to reach the desired goals of this project.

2.5.1 Initial Research

To begin movement beyond the feasibility and parameters for this project, initial research was conducted in order to determine what exactly the team was trying to produce, and how we would go about doing so. While keeping the project goals, and project constraints in mind, the main topics of initial research included the research of recycling and aluminum stripping of used beverage cans, the chemical reactions used to turn aluminum into aluminum oxynitride powder, the equipment and designs necessary to carry out the synthesis, and finally, the marketability of the substance. The research was conducted primarily through the use of the research database
During the initial research phase of this project, numerous different alternatives for each topic of discussion were discovered.

2.5.2 Analysis of Design Alternatives

The main purpose of this project is to develop the optimal process to allow for cost effective production of AlON. This can be accomplished by analyzing all possible design alternatives for each portion of the project as discussed above, and analyzing how each decision will affect the outcomes of the product as well as the economics of the overall process. After in-depth investigation, the best alternative for each portion of the project was chosen, and the most optimal case in each area is discussed below.

2.5.3 Process Design

The process design portion of the project involved the specific details of how the product would be made in an industrial scale. Once the optimal synthesis route was determined, the focus shifted towards how it could be physically implemented into a chemical plant. This portion of the project therefore revolved around the process itself, and the equipment necessary for AlON production.

2.5.4 Optimization

In order to maximize the profits for the plant being designed, the design must be optimized by optimizing equipment and operating conditions. The most important systems to optimize were the two atomizing reactor systems since they are the main portions of the design and require large amounts of energy inputs. The optimization procedure will be explained in detail further on in this report.
3 Initial Research

3.1 Aluminum Feed

Taking used aluminum beverage cans for the feedstock in this process is the most significant way in which the cost of producing AlON can be lowered, assuming these cans are cheap and readily available. In order to determine if this is in fact a feasible starting material, a calculation was performed which estimated the number of cans necessary to produce a given quantity of AlON.

With production goals being to produce approximately 100 gallons of AlON powder per day, the amount of cans recycled in the Grand Rapids area was used as a basis for production calculations. Every year in Grand Rapids, roughly 33 million cans are recycled. At approximately .95 grams Al/gram, there is on average 11.9 grams of pure aluminum in every can. This equates to 390,000 kg of aluminum that could potentially be recovered from recycled cans every year in the Grand Rapids area. Assuming a basis of recycling 60% of the total recycled cans in Grand Rapids, this results in an amount of 236,000 kg aluminum to be used for production into AlON. The AlON powder which will be produced in this process is 56% aluminum by weight. With the basis of 236,000 kg of aluminum recovered, 422,000 kg of AlON powder can be produced from these cans. Using 422,000 kg of AlON powder equates to approximately 450 tons, which will be used as the initial goal for production. 450 tons of AlON powder per year broken down, is approximately 100 gallons of powder per day. This value is a very feasible daily and yearly amount, attainable in an average industrial production facility. These calculations show that it is in fact feasible to begin this process with aluminum cans. The usage of a sustainable percentage of the cities recycled cans shows not only room for growth within the city, but also that there could be potential growth from bringing cans from surrounding cities.
3.2 Aluminum Extraction

Aluminum extraction from new cans is not a new process, and has been utilized for years. There are, however, different ways of doing this. Before the aluminum cans are melted, they must first be either mechanically or chemically stripped in order to remove paint, dirt, and other contaminants. These alternatives found during research will be analyzed to determine the best process of extracting aluminum from the cans.

3.3 Synthesis Options

Knowing the final product required and the feedstock, it was possible to determine many viable series of chemical reactions that would fulfill the requirements of this project. The initial research resulted in a list of 9 different synthesis routes for AlON, all of which can be seen in Table 1 below.

Table 1 - Chemical Reactions known to produce aluminum oxynitride

<table>
<thead>
<tr>
<th>Synthesis equation</th>
<th>Required temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Al}_2\text{O}_3(s) + \text{AlN}(s) \rightarrow \text{AlON}(s)$</td>
<td>$\geq 1650°C$</td>
</tr>
<tr>
<td>$\text{Al}_2\text{O}_3(s) + \text{C}(s) + \text{N}_2(g) \rightarrow \text{AlON}(s) + \text{CO}_2(g)$</td>
<td>$\geq 1700°C$</td>
</tr>
<tr>
<td>$\text{Al}_2\text{O}_3(s) + \text{C}(s) + \text{Air} \rightarrow \text{AlON}(s) + \text{CO}_2(g)$</td>
<td>$\geq 1700°C$</td>
</tr>
<tr>
<td>$\text{Al}_2\text{O}_3(s) + \text{Al}(l) + \text{N}_2(g) \rightarrow \text{AlON}(s) + \text{CO}_2(g)$</td>
<td>$\geq 1500°C$</td>
</tr>
<tr>
<td>$\text{Al}_2\text{O}_3(s) + \text{Al}(l) + \text{Air} \rightarrow \text{AlON}(s)$</td>
<td>$\geq 2045°C$</td>
</tr>
<tr>
<td>$\text{Al}_2\text{O}_3(s) + \text{NH}_3(g) + \text{H}_2(g) \rightarrow \text{AlON}(s) + \text{H}_2\text{O}$</td>
<td>$\geq 1650°C$</td>
</tr>
<tr>
<td>$\text{Al}(l) + \text{Air} \rightarrow \text{AlON}(s)$</td>
<td>$\sim 1500°C$</td>
</tr>
<tr>
<td>$\text{AlCl}_3(g) + \text{CO}_2(g) + \text{NH}_3(g) + \text{N}_2(g) \rightarrow \text{AlON}(s) + \text{CO}_2(g) + \text{N}_2(g) + \text{HCl(g)}$</td>
<td>900°C</td>
</tr>
<tr>
<td>$\text{Al}_2\text{O}_3(s) + \text{BN}(s) + \text{N}_2(g) \rightarrow \text{AlON}(s)$</td>
<td>$\geq 1700°C$</td>
</tr>
</tbody>
</table>

As can be seen in the table above, there are many different reactants that can be used in order to

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create aluminum oxynitride. This table does not show balanced reactions, rather a demonstration of the required reactants and the phases of these reactants. Another additional note from this table is the required temperature for each reaction, almost all of the reactions require different temperatures. These temperatures are directly related to operating costs through the energy required to reach the specific temperatures, resulting in an additional design parameter.

3.4 Structure and Properties of AlON Transparent Ceramic

The structure of the AlON powder produced has a large impact on the properties of the resulting ceramic made from it. In order to ensure the process developed in this project will produce powder meeting the necessary requirements, the different structures of AlON and the properties which they affect had to be determined.

3.4.1 Structure and Properties of AlON Transparent Ceramic

If the correct ratio of reactants is reacted to produce AlON powder, the transparent aluminum ceramic should have a cubic, spinel structure. This structure gives the ceramic its strength. As seen in Table 2 below, AlON transparent aluminum has strength and hardness properties much greater than average materials such as silica, which is used to make glass. Also, it can be noted that AlON has relatively comparable properties to sapphire, which is known to be an extremely strong material. In addition to its strength, AlON ceramic has desirable thermal properties allowing it to resist melting and brittleness due to heat change.
Table 2-Properties of ALON

<table>
<thead>
<tr>
<th>PROPERTIES</th>
<th>UNITS</th>
<th>ALON™</th>
<th>Sapphire</th>
<th>Quartz (fused silica)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>g/cc</td>
<td>3.69</td>
<td>3.97</td>
<td>2.21</td>
</tr>
<tr>
<td>Grain Size</td>
<td>Micrometers</td>
<td>150-250</td>
<td>single crystal</td>
<td>amorphous</td>
</tr>
<tr>
<td>Color</td>
<td>Transparent</td>
<td>Transparent</td>
<td>Transparent</td>
<td>Transparent</td>
</tr>
<tr>
<td>Flexural Strength</td>
<td>MPa (ksi)</td>
<td>379 (55)</td>
<td>742 (107.7)</td>
<td>48 (7)</td>
</tr>
<tr>
<td>Fracture Toughness</td>
<td>MPa-m^1/2</td>
<td>2 (indentation method)</td>
<td>2</td>
<td>0.8</td>
</tr>
<tr>
<td>Compressive Strength</td>
<td>MPa (ksi)</td>
<td>2677 (388) (see note 1)</td>
<td>650 - 1100</td>
<td></td>
</tr>
<tr>
<td>Hardness</td>
<td>(kg/mm²)</td>
<td>1850</td>
<td>2000</td>
<td>460</td>
</tr>
<tr>
<td>Elastic Modulus</td>
<td>GPa (psi x 10⁶)</td>
<td>334 (48.4)</td>
<td>344 (49.8)</td>
<td>70 (10.1)</td>
</tr>
<tr>
<td>Shear Modulus</td>
<td>psi x 10⁶</td>
<td>135 (19.6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>W/m-K (cal/cm-s-c°C)</td>
<td>9.5 (0.023)</td>
<td>36</td>
<td>1.6</td>
</tr>
<tr>
<td>Specific Heat</td>
<td>(J/g-K) (Cal/g-°C)</td>
<td>0.77 (0.22)</td>
<td>0.75 (0.21)</td>
<td>0.22</td>
</tr>
</tbody>
</table>

The final property that makes this ceramic appealing is its transparency. As seen in the graph below, ALON ceramic allows approximately 90% of light through at a wide range of wavelengths.

![Figure 3-Transpareancy of ALON](image)

Visible light has a wavelength around 550 nm, which equals 0.5 microns. The graph shows that at this wavelength ALON ceramic lets about 85% of light through a 2 mm thick sample. These
transparent and strength properties are what make this material a great choice for armor and defense applications.

4 Analysis of Design Alternatives

4.1 Aluminum Extraction Method

Aluminum cans collected from collection sites will first be shredded into small pieces. After shredding, these scraps must be cleaned and stripped of contaminants by one of the following methods. The first option for cleaning the scraps involves a mechanical process which physically scrapes and rubs the contaminants off of the scraps using friction. This process would be carried out in a large rotating drum. The second method for cleaning the scraps is using a chemical bath to remove and paint or contaminants. Once the scraps have been cleaned and stripped of paint, they will be fed to a furnace to melt them. The aluminum can then be extracted from the liquid metal mixture based on differences in density between the different metals in the can.

4.2 Production Process

The production of AlON powder can be performed in many different ways as discussed above. The design alternatives were analyzed in order to determine the optimal route for producing the AlON powder. This section outlines the major design decisions, and the processes that will be used as a result.

4.2.1 Synthesis Route

After discovering the numerous pathways of producing the aluminum oxynitride, choosing the optimal route for production was a key decision in this design project. The table showing all of these various pathways can be seen above in Table 1. The decision for the optimal chemistry route comes down to factors such as availability and cost reactants, required temperature (and therefore energy) for each particular chemistry, the waste products produced, and the phase of the reactants
in each chemistry. Upon initial evaluation of the multiple types of chemistries, the original selection for synthesis route was the eighth option seen in Table 1, which synthesizes AlON through a method called chemical vapor deposition, essentially taking gaseous aluminum chloride, and through the chemical reaction, AlON would be created. This route was deemed ideal due to its significantly lower reaction temperature, and utilization of gaseous reactants. However upon further research, and discussions with our industrial mentors, it was determined that this route would not produce AlON in quantities large enough. Due to the fact that it is vapor deposition, only a thin layer of AlON would form, this method is used primarily as a coating technique, as opposed to a large quantity production method. Therefore, it was determined that reaction number 1 seen in Table 1 was the best synthesis route to produce AlON. This route is the one that is currently used in manufacturing of AlON, and therefore the research available for this reaction was the most available. It was found that this route is the most common way to produce AlON due to its simplicity. Once the reactants of aluminum nitride and aluminum oxide are procured, the reaction process to create the AlON is straight forward and painless.

In this reaction, aluminum oxide (alumina) reacts with aluminum nitride in a solid state reactor. This reaction must take place at very high temperatures, above 1600 C. The exact temperature will be decided through the optimization portion of the project, as there is a tradeoff between the reactor temperature and the ratio of reactants fed to the reactor. As seen in Table 3 below, varying the ratio of the reactants will produce a different form of AlON, potentially providing an undesired AlON structure.
In order to achieve the AlON with the necessary spinel structure containing the desired properties, the gamma ($\gamma$) version of AlON is needed. This structure requires the starting reactants to be present in approximately 36 mol % aluminum nitride and 64 mol % aluminum oxide. When the correct ratio of these reactants is obtained, the two reactants need to be mixed prior to entering the reactor in order to maximize the contact between the two substances. The various other phases present in this pseudo-binary system all represent phases with varying crystallographic structures. These alternate phases can be seen in the phase diagram in the Figure below.

Table 3-Different AlON Powder Structures$^5$

<table>
<thead>
<tr>
<th>Notation</th>
<th>Mol% AlN</th>
<th>Formula</th>
<th>Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>2H</td>
<td>100</td>
<td>AlN</td>
<td>Polytype</td>
</tr>
<tr>
<td>32H</td>
<td>93.3</td>
<td>Al$_{16}$O$<em>3$N$</em>{14}$</td>
<td>Polytype</td>
</tr>
<tr>
<td>2H$^6$</td>
<td>~91</td>
<td>Al$_{12}$O$<em>3$N$</em>{10}$</td>
<td>Polytype</td>
</tr>
<tr>
<td>20H</td>
<td>88.9</td>
<td>Al$_{10}$O$_3$N$_8$</td>
<td>Polytype</td>
</tr>
<tr>
<td>27R</td>
<td>87.5</td>
<td>Al$_9$O$_3$N$_7$</td>
<td>Polytype</td>
</tr>
<tr>
<td>16H</td>
<td>85.7</td>
<td>Al$_8$O$_3$N$_6$</td>
<td>Polytype</td>
</tr>
<tr>
<td>21R</td>
<td>83.3</td>
<td>Al$_7$O$_3$N$_5$</td>
<td>Polytype</td>
</tr>
<tr>
<td>12H</td>
<td>80.0</td>
<td>Al$_6$O$_3$N$_4$</td>
<td>Polytype</td>
</tr>
<tr>
<td>$\gamma$-AlON</td>
<td>35.7</td>
<td>Al$<em>{23}$O$</em>{27}$N$_5$</td>
<td>Spinel</td>
</tr>
<tr>
<td>$\gamma'$-AlON</td>
<td>~21.0</td>
<td>Al$<em>{19.7}$O$</em>{29.5}$N$_{2.5}$</td>
<td>Spinel</td>
</tr>
<tr>
<td>$\phi'$-AlON</td>
<td>16.7</td>
<td>Al$<em>{22}$O$</em>{30}$N$_2$</td>
<td>Spinel</td>
</tr>
<tr>
<td>$\delta$-AlON</td>
<td>10</td>
<td>Al$<em>{19}$O$</em>{27}$N</td>
<td>Spinel</td>
</tr>
<tr>
<td>$\phi$-AlON</td>
<td>7.1</td>
<td>Al$<em>{27}$O$</em>{39}$N</td>
<td>Monoclinic</td>
</tr>
<tr>
<td>$\alpha$-Al$_2$O$_3$</td>
<td>0</td>
<td>Al$_2$O$_3$</td>
<td>Rhombohedral</td>
</tr>
</tbody>
</table>

These structures are insufficient in providing appropriate properties of transparency and strength due to their packing factors of atoms.

4.2.2 Producing the Reactants

Once the AlON synthesis route was determined, the process needed to produce the required reactants needed to be designed. Since this entire project begins by recycling cans into molten

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aluminum, it was determined that atomizing reactors were a good design to turn molten aluminum into the two necessary reactants in powder form. The details of this process will be discussed later in the process design section. Also, the way in which these atomizers were modeled needed to be determined. Although this is a batch system since aluminum is manually loaded into the reactors in batches, the reaction occurs in an environment that closely resemble a flow system. When the aluminum is sprayed into the reactor and falls downward, it reacts with the gas. Since the reaction occurs as the aluminum moves down the length of the reactor and aluminum is being continuously sprayed into the reactor during a given batch, the system most closely resembles as a flow system. This allows the atomizing reactors to be modeled as plug-flow reactors (PFRs).

5 Process Design

Once all of the requirements for the reaction sequence were specified, the required stages of the process were able to be determined. This resulted in a complete flow sheet throughout the AlON production process, and a fully encompassing equipment list.

5.1 Process Flow Diagram

This process flow diagram shows the entire process for the synthesis of AlON powder from aluminum UBCs. As shown, the diagram is split into three sections: recycle process, reactant production process, and AlON synthesis process.
5.2 Equipment

As mentioned previously, this section highlights the fully encompassing industrial equipment list for the process, and descriptions for each component. The cost of each piece of equipment was estimated using the design book and the energy that would be used in each piece. Below, the equipment can be seen showing the temperatures and pressures of each piece of equipment. The price of each piece of equipment was estimated using equations from one of the design books. If no equation is specified, the cost was estimated using the excel sheet attached to the Turton design book.  

---


Table 4- Equipment List

<table>
<thead>
<tr>
<th>Equipment Name</th>
<th>Description</th>
<th>Energy Used</th>
<th>Operating Pressure</th>
<th>Operating Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Can Shredder</td>
<td>Shred incoming cans</td>
<td>Electricity</td>
<td>Atmospheric</td>
<td>25 C</td>
</tr>
<tr>
<td>Aluminum Furnace</td>
<td>fired heater which melts aluminum into molten form</td>
<td>natural gas</td>
<td>Atmospheric</td>
<td>750 C</td>
</tr>
<tr>
<td>AlIN Reactor (insulated)</td>
<td>reacts aluminum and nitrogen in a PFR reactor</td>
<td>natural gas</td>
<td>40 PSIG</td>
<td>885 C</td>
</tr>
<tr>
<td>Al$_2$O$_3$ Reactor (insulated)</td>
<td>reacts aluminum and oxygen in a PFR reactor</td>
<td>natural gas</td>
<td>40 PSIG</td>
<td>232 C</td>
</tr>
<tr>
<td>AlIN Reactor Vortex Separator</td>
<td>separates powder and gas</td>
<td>N/A</td>
<td>Atmospheric</td>
<td>~800 C</td>
</tr>
<tr>
<td>Al$_2$O$_3$ Reactor Vortex Separator</td>
<td>separates powder and gas</td>
<td>N/A</td>
<td>Atmospheric</td>
<td>~200 C</td>
</tr>
<tr>
<td>Nitrogen Compressor</td>
<td>Compress Nitrogen gas</td>
<td>Electricity</td>
<td>40 PSIG</td>
<td>253 C</td>
</tr>
<tr>
<td>Oxygen Compressor</td>
<td>Compress Oxygen gas</td>
<td>Electricity</td>
<td>40 PSIG</td>
<td>79 C</td>
</tr>
<tr>
<td>Nitrogen Heater</td>
<td>Heat up nitrogen feed to AlIN reactor</td>
<td>natural gas</td>
<td>40 PSIG</td>
<td>885 C</td>
</tr>
<tr>
<td>Oxygen Heater</td>
<td>Heat up oxygen feed to Al$_2$O$_3$ reactor</td>
<td>natural gas</td>
<td>40 PSIG</td>
<td>232 C</td>
</tr>
<tr>
<td>Nitrogen gas filter</td>
<td>Filters recycled gas</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Oxygen gas filter</td>
<td>Filters recycled gas</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Cryogenic Air Separation Unit</td>
<td>Separates air into pure Nitrogen and Oxygen</td>
<td>Electricity</td>
<td>75 PSIG</td>
<td>-185 C</td>
</tr>
<tr>
<td>Ball Mixer</td>
<td>Mixes reactants before entering AION reactor</td>
<td>Electricity</td>
<td>Atmospheric</td>
<td>N/A</td>
</tr>
<tr>
<td>AION Solid State Reactor</td>
<td>Stirred batch reactor that produces AION powder</td>
<td>Natural gas</td>
<td>Atmospheric</td>
<td>1800 C</td>
</tr>
</tbody>
</table>

5.2.1 Can Shredder

This shredder will effectively turn cans into small shreds of aluminum cans which can then be fed to the furnace. This can shredder has rotating steel teeth to shred the cans. Shredders used for this purpose are widely available from many different vendors, and can more than handle the capacity which this design will need.
5.2.2 Aluminum Furnace

This furnace will melt the previously shredded cans, heating the metal scraps to 750 degrees C by burning natural gas. This process will be performed in an oxygen deficient environment by filling the furnace with nitrogen. If oxygen were present as the aluminum began to melt, the molten aluminum would oxidize. 750 degrees is hot enough to melt the aluminum scraps but not hot enough to allow nitration to occur.

5.2.3 Vortex Separators

Upon completion of the atomizing reactors, gas and powder will be effectively separated in a vortex separator. The nitrogen or oxygen stream enters into a conical container, at which point it begins to flow in a helical pattern. As the gas travels in its rotating motion, the heavier powder particles crash into the walls of the separator since they have too much inertia to turn with the gas. The dust particles then fall to the bottom opening of the separator where they are collected. The clean gas then rises to the top of the separator and out the top when it begins to get constricted by the smaller bottom section of the separator. These separators were priced as dust collectors, since they are very similar in design and dust collector pricing is much more available. The price depended on the flow rate of gas entering the separator. The nitrogen separator had an entering flow rate of 0.097 m³/sec giving a price of $5,980. Meanwhile, the oxygen separator had an entering flow rate of 0.065 m³/sec giving a price of $5,070.

5.2.4 Cryogenic Air Separation Unit

This unit separates air into its natural components, both pure oxygen and pure nitrogen that are required in the atomization processes. This is done by utilizing the differences in boiling points of the components in dry air, which can be seen in Table 5, and separating them in a distillation column.
### Table 5- Components of dry air⁹

<table>
<thead>
<tr>
<th>Gas</th>
<th>% by Volume</th>
<th>% by Weight</th>
<th>Parts per Million (V)</th>
<th>Chemical Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>78.08</td>
<td>75.47</td>
<td>760805</td>
<td>N₂</td>
</tr>
<tr>
<td>Oxygen</td>
<td>20.95</td>
<td>23.20</td>
<td>209450</td>
<td>O₂</td>
</tr>
<tr>
<td>Argon</td>
<td>0.93</td>
<td>1.28</td>
<td>9340</td>
<td>Ar</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>0.039</td>
<td>0.0606</td>
<td>390</td>
<td>CO₂</td>
</tr>
</tbody>
</table>

This unit will be installed, operated, and maintained by a third party company, minimizing need for much attention, and the result is a constant reliable stream of high purity gases. A broad schematic of the separation process can be seen in the Figure below.

Figure 6- Process flow diagram for air separation unit¹⁰

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This unit will come with an upfront capital cost of roughly $1.2 Million, for installation of the equipment. In addition, the cost for using this system will be an annual operating cost, which includes the price of power, labor, maintenance, and insurance on the equipment. This value results in approximately $650,000/yr.  

5.2.5 Nitrogen and Oxygen Compressors

These compressors are responsible for compressing the nitrogen and oxygen gas to the desired 40 PSIG. Since this is not an extremely high pressure, these compressors were priced as screw compressors which are much cheaper than centrifugal compressors. Using cost equation 2 in the appendix, the capital cost of each compressor was determined based on the necessary horsepower. The energy needed to run each compressor was determined from UNISIM software, and assumed to be received via electricity since these compressors are not incredibly large. Assuming 60% efficiency, the nitrogen compressor required 89 horsepower yielding a capital cost of $104,460. Again assuming 60% efficiency, the oxygen compressor required 44 horsepower giving a capital cost of $58,797.

5.2.6 Nitrogen and Oxygen Heaters

These heaters heat the nitrogen and oxygen to the desired temperatures before entering the atomizing reactors. The nitrogen must be heated to a temperature of 885 degrees Celsius, while the oxygen only needs to be heated to 232 degrees Celsius. These heaters were priced as fired heaters, using natural gas as the fuel. The capital cost of these heaters was determined using cost equation number 1 seen in the appendix, which estimates the base cost of the heater based on the energy that the heater will need to output. The nitrogen heater uses 286,345 btu/hr giving a capital cost of $104,460.
cost of $35,548. The oxygen heater uses only 44,227 btu/hr giving a capital cost of $8,500.

5.2.7 Nitrogen and Oxygen Filters

The atomizing reactors utilize pressurized gas being sprayed into the molten aluminum, so after the gases are used they will be recycled back through the apparatus to save resources. The gasses will first run through the vortex separators, but will then pass through these filters to ensure no debris is passed into the compressors, since this would ruin a compressor. Using an area of 0.5 ft$^2$ for each filter, the capital cost was determined to be

5.2.8 Nitrogen and Oxygen Atomizing Reactors

These two reactors will be used to generate the reactants needed to produce AlON (AlN and Al2O3). The volume of these reactors will be determined by estimating rate laws for both oxidation and nitridation of aluminum. The reaction chosen to make AlON for this project requires aluminum oxide and aluminum nitride as reactants in powder form. Both of these reactants will be made from the aluminum recovered from the recycled beverage cans. These reactants can be made through a process called atomizing. Atomizing allows the molten aluminum leaving the recycling process to react to the desired reactant and take a powder form simultaneously. A diagram of this atomizing process can be seen below in Figure 7$^{12}$.

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Team 09 will have 2 apparatuses as seen above; one to produce aluminum nitride powder and one to produce aluminum oxide powder. The molten aluminum exiting the recycling process will be dumped into each atomizer from the top. Once the aluminum is poured into the atomizer, the lid (5) will be closed and the space above the molten aluminum (1) as well as the atomizing chamber (7) will be filled with pressurized pure nitrogen gas in the AlN atomizer and pure oxygen gas in the Al₂O₃ atomizer. The gas in each atomizer system will be pressurized to 40 PSIG in a compressor (12) prior to entering. The pressurized gas will enter the atomizing chamber through a nozzle (6) which forces the gas at high velocity to flow by the aluminum entering the chamber through the spout (4). This interaction between aluminum and the gas allows the reaction to take place. In the case of the AlN atomizer, the nitrogen gas in the atomizing chamber (7) must be heated to a temperature greater than 800 C. Below 800 C, nitrogen will not react with aluminum in a reasonable amount of time since it is a very inert molecule, causing the reactor to require a large volume. In the case of the oxygen atomizer, the oxygen only needs to be heated to greater than 200
C since aluminum oxidizes very readily at lower temperatures. This also allows for essentially
100% conversion of aluminum to aluminum oxide since this reaction occurs very easily. When the
material reaches the bottom of the chamber, it will be swept into a vortex separator which
effectively separates the gas from the powder, allowing the gas to be recycled.
In order to determine the size of atomizing reactors needed, both the AlN reactor and the Al$_2$O$_3$
reactor were modeled as plug-flow reactors (PFR’s). Each atomizing reactor was modeled using
the PFR design equation seen below:

$$V = F_0 \int_0^x \frac{1}{-r_a} dx$$

Where $F_0$ is the flow of reactants entering the reactor, $x$ is conversion, $V$ is reactor volume, and $r_a$
is the reaction rate law. In both reactors, 99% conversion was required and therefore $x = 0.99$ in
this model. The reaction rate law for both reactions was found to be a zero order reaction, and
therefore the reaction rate=$k$. The rate constant, $k$, was estimated at different temperatures based on
research articles. The estimated rate constant for the aluminum and nitrogen reaction can be seen
below:

$$k = 4.2 \times 10^{10} e^{-63,700/RT}$$

Where $R$ is the gas constant and $T$ is the temperature in Celsius. Similarly, the aluminum and
oxygen reaction rate can be described by the rate constant below:

$$k = 2.34 \times 10^{11} e^{-47,700/RT}.$$  

Looking at these two rate constants, it can be seen that the Al-O reaction will occur much faster
since the K value will be much larger at a given temperature. This is consistent with expectations
since oxygen readily reacts with aluminum, while nitrogen is a rather inert molecule.
Since $k$ varies with temperature, it was possible to find the optimal operating temperature for each
atomizing reactor. This procedure and the optimization results will be further discussed in the optimization section of the report.

In order to determine parameters for the atomizing reactors such as atomization rate, the following equation was used:

\[ Q = \sqrt{\frac{2g(H + L - \Delta P)}{\gamma} f \left( \frac{L}{D} \right) + k + 1} \]

Where \( Q \)= atomization rate in L/s, \( g \)= gravity, \( H \)= height of aluminum in delivery tank, \( L \)= length of delivery nozzle, \( \Delta P \)= change in pressure from top of aluminum to bottoms of delivery nozzle, \( \gamma \)= (density of aluminum)*g, \( f \)= friction factor, \( D \)= diameter of delivery nozzle, \( k \)= gas entrance loss, and \( A \)= cross sectional area of delivery nozzle. Many of these parameters were either known or estimated from research, and it was decided that the diameter of the delivery nozzle was a key design variable. Since the amounts of AlN and Al\(_2\)O\(_3\) required were known based on the yearly goal of 450 tons of ALON, the rate of atomization for both reactors was calculated based on 3000 hours of operation per year: 0.0115 L/s or 41.5 L/hr. The diameter of the delivery nozzle could then be varied until an adequate atomization rate was achieved, keeping the diameter under 10 mm. This was the largest atomizing nozzle found during research and therefore was considered to be the upper bound of nozzle size. A nozzle diameter of 8 mm was chosen. The other parameters and reactor sizes can be seen below.
Table 6 – Atomizer Specifications

<table>
<thead>
<tr>
<th>Atomizing Reactor Specifications</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AlN Reactor Size:</strong></td>
<td>2.87 ft diameter, 10.5 ft tall</td>
</tr>
<tr>
<td><strong>Al2O3 Reactor Size:</strong></td>
<td>2.15 ft diameter, 6.3 ft tall</td>
</tr>
<tr>
<td><strong>Spray Angle:</strong></td>
<td>45°</td>
</tr>
<tr>
<td><strong>Nozzle Diameter:</strong></td>
<td>8 mm</td>
</tr>
<tr>
<td><strong>Atomization Rate:</strong></td>
<td>41.5 Liters/hr</td>
</tr>
</tbody>
</table>

These atomizing reactors were priced as vertical pressure vessels since they are essentially vertical tanks. They were designed to handle pressure because the nitrogen and oxygen entering them is under pressure. If the outlet streams were to get plugged for some reason, the reactors need to be able to withstand the 40 PSI of the entering gas. Using cost equation 3, the capital cost of the AlN reactor was determined to be $121,208 and the capital cost of the Al2O3 reactor was determined to be $35,518.

5.2.9 Ball Mixer

This piece of equipment takes AlN powder and Al2O3 powder and completely mixes them together. This mixer runs on electricity, and simply rolls the two powders until the crystals are fully embedded within each other. There is no temperature or pressure requirements for this step, as it is a simple mixture mechanism and no reaction is taking place. This is the preparation step before the mixture is sent to the reactor to be transformed into AlON. The AlN and Al2O3 powder
leaving the atomizers will travel to a ball mill, where the two reactants will be adequately mixed. The proposed mixing mechanism, a ball mill, can be seen in Figure 8 below.

![Sample Ball Mill](image)

**Figure 8-Sample Ball Mill**

This style of mixer is very effective and commonly used for mixing powders, which is why it was chosen. Inside of this ball mixer will contain the proportionate amount of powders discussed above to create the desired phase of AlON, as well as multiple Si₃N₄ balls, and finally a mixing medium of isopropanol. Research showed that the Si₃N₄ balls and isopropanol were be optimal mixing agents for the two reactants.¹³

### 5.2.10 AlON Solid State Reactor

This is where the AlN and Al₂O₃ react into AlON. Both reactants enter in the solid, powder form, premixed from the ball mixer. The reactants are heated to the reaction temperature of 1800 degrees Celsius, where the reaction occurs. The product from this reactor is the final product from the process, the AlON powder, which can be then used for further manipulation. This reactor is a stirred batch reactor. As seen in the figure below, 1800 degrees C was chosen as the reaction temperature because 100% conversion can be achieved at this temperature. Since this is the final product and the AlON powder needs to be pure in order to produce the correct properties in the ceramic, it was decided to run this reaction at 1800 degrees C.

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It should be noted that the figure above is based on a 2.5 hour batch time, which is the minimum amount of time required for the reaction to go to completion. If a lower temperature were to be used, the time to reach 100% conversion drastically jumps up.

6 Optimization

In order to maximize profitability for this plant, the process needed to be optimized. The three reactors and their surrounding equipment are the primary systems that needed to be optimized.

6.1 AlN Reactor System

The aluminum nitride reactor system includes the reactor itself as well as the heater that will be used

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to heat the nitrogen gas to the desired reaction temperature. Pricing the reactor as a pressure vessel, since the entering gas is pressurized, and the heater as a fired heater, it was possible to determine an optimal operating temperature for this system. As the temperature increased, the heating costs obviously increased, but the reaction occurred quicker and therefore a smaller reactor was required. The total annual cost of the reactor system was evaluated at various temperatures, and the lowest cost was chosen. As seen in Figure 5 below, the optimal temperature was 885 C.

![AlN Reactor Optimization Curve](image)

Figure 10-AlN Reactor Optimization

Operating at 885 C gave a required reactor volume of 68 ft³. Since the diameter has a greater effect on the price than the height, the diameter set lower than the height. The reactor will have a diameter of 2.87 feet and a height of 10.5 feet.

### 6.2 Al₂O₃ Reactor System

The same procedure was used as the AlN reactor system. The vessel was priced as a pressure vessel and the heating costs of heating the oxygen to the required temperature was also taken into
account. The optimization graph for this reactor system can be seen below.

![Al₂O₃ Reactor Optimization Curve](image)

**Figure 11-Al₂O₃ Reactor Optimization**

The optimal temperature for this reactor was 232 degrees C. At this temperature, a reactor volume of 23 ft³ was necessary. This reactor had a diameter of 2.15 feet, and a height of 6.3 feet. This reactor is much smaller and operating at much lower temperatures than the AlN reactor since oxygen reacts very readily with aluminum, unlike nitrogen which is a very inert molecule.

### 7 Economics

This economics section will highlight the overall economic analysis for the plant implementation. With sections highlighting both the capital costs and the annual operating costs, this section will include all costs and expenses that this new plant will contain throughout its estimated 25 year life. In addition, there is a section comparing the sale price of AlON powder via this synthesis process to the estimated price of powder that Surmet would possess.
7.1 Capital Costs
This section will encompass all capital costs that are used in the creation of this chemical plant. This includes all equipment, as well as building costs. These costs are all displayed as both a total initial cost, as well as a capital cost annuity. By displaying the cost annuity, it is possible to evaluate the overall costs of materials on an annual basis, taking into account the value of money throughout the years in order to calculate the equivalent annual operating cost (EAOC).

Table 7-Equipment Capital Costs

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Capital Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlN Reactor</td>
<td>$122,000.00</td>
</tr>
<tr>
<td>Al₂O₃ Reactor</td>
<td>$88,792.00</td>
</tr>
<tr>
<td>Recycling Furnace</td>
<td>$672,500.00</td>
</tr>
<tr>
<td>Nitrogen Heater</td>
<td>$36,000.00</td>
</tr>
<tr>
<td>Oxygen Filter</td>
<td>$5,148.66</td>
</tr>
<tr>
<td>Nitrogen Filter</td>
<td>$2,060.00</td>
</tr>
<tr>
<td>Oxygen Heater</td>
<td>$21,250.73</td>
</tr>
<tr>
<td>Cryogenic Air Separation Unit</td>
<td>$1,200,000.00</td>
</tr>
<tr>
<td>Nitrogen Compressor</td>
<td>$104,460.00</td>
</tr>
<tr>
<td>Oxygen Compressor</td>
<td>$146,993.00</td>
</tr>
<tr>
<td>Can Shredder</td>
<td>$160,000.00</td>
</tr>
<tr>
<td>AlON Reactor</td>
<td>$307,000.00</td>
</tr>
<tr>
<td>Ball Mixer</td>
<td>$51,000.00</td>
</tr>
<tr>
<td>AlN Vortex Separator</td>
<td>$5,980.00</td>
</tr>
<tr>
<td>Al₂O₃ Vortex Separator</td>
<td>$5,070.00</td>
</tr>
<tr>
<td>Total Capital Cost</td>
<td>$2,928,254.39</td>
</tr>
</tbody>
</table>

7.2 Annual Operating Costs
This section includes all costs that this plant will incur throughout any given year of production. Due to the fact that the process of producing AlON is incredibly energy intensive, the annual operating costs are large and even outweigh the initial capital cost. These annual costs can be seen in the tables below.
Table 8-Annual Operating Costs

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Annual Operating Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>AION Reactor</td>
<td>$2,498,349.00</td>
</tr>
<tr>
<td>Recycling Furnace</td>
<td>$443,935.00</td>
</tr>
<tr>
<td>Nitrogen Heater</td>
<td>$2,732,299.00</td>
</tr>
<tr>
<td>Oxygen Heater</td>
<td>$422,511.00</td>
</tr>
<tr>
<td>Nitrogen Compressor</td>
<td>$17,193.00</td>
</tr>
<tr>
<td>Oxygen Compressor</td>
<td>$8,381.00</td>
</tr>
<tr>
<td>Can Shredder</td>
<td>$38,880.00</td>
</tr>
<tr>
<td>Total Annual Operating Cost</td>
<td>$6,161,548.00</td>
</tr>
</tbody>
</table>

Table 9-Annual Material Costs

<table>
<thead>
<tr>
<th>Material</th>
<th>Price per Kg</th>
<th>Flowrate (Kg/hr)</th>
<th>Annual Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>$0.16</td>
<td>312.81</td>
<td>$150,148.80</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>$0.40</td>
<td>409.39</td>
<td>$491,268.00</td>
</tr>
<tr>
<td>Aluminum Cans</td>
<td>$0.55</td>
<td>173.86</td>
<td>$286,869.00</td>
</tr>
<tr>
<td>AION Powder</td>
<td>$30.00</td>
<td>140.82</td>
<td>$12,673,800.00</td>
</tr>
</tbody>
</table>

7.3 AION Powder Cost Conclusions

With the original goal for this project being to minimize the cost of AION production to stimulate the commercialization of AION ceramic, it is important to compare this processes cost to produce the powder to a comparable cost value. One way in which this was achieved was by starting the process with aluminum cans rather than aluminum. The current market price of aluminum is $0.77 per pound, but it was determined that after aluminum is extracted from used beverage cans, the recycled aluminum would only cost $0.60 per pound. This price includes the cost of cans as well as the energy required to extract pure aluminum from the cans. The sale of AION powder is not a marketplace that currently exists, and Surmet is the only company that even produces the powder, which they immediately press it into ceramic without putting a price tag on it. Therefore in order to estimate the value of the powder that Surmet uses, a back calculation was performed based on the cost of the AION ceramic, and the estimated costs of hot pressing their powder into that ceramic. It
was estimated that the Surmet powder would cost $58.65 per kg based on their ceramic price. Our break-even price for this project was determined to be $11.22 per kg of AlON powder. Based on these prices, our powder would be sold for $30 per kg, allowing us to be cheap enough to break into a new market will still being cheaper than what would currently be on the market. This selling price would yield an annual product revenue of $12.7 million. As seen in the table below, the EAOC value turns out to be negative meaning this company would make money.

<table>
<thead>
<tr>
<th>Cost</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital</td>
<td>$ 2,928,254.39</td>
</tr>
<tr>
<td>Annual Operating</td>
<td>$ 6,161,548.00</td>
</tr>
<tr>
<td>Annual Materials</td>
<td>$ 929,371.54</td>
</tr>
<tr>
<td>Annual Product Revenue</td>
<td>$ 12,673,800.00</td>
</tr>
<tr>
<td>EAOC</td>
<td>($ 5,129,881.26)</td>
</tr>
</tbody>
</table>

It should be noted that this EAOC and annual operating cost does not include property tax or costs, labor, or any other employee benefits. In order to estimate these things, the design book excel model\textsuperscript{15} was used to determine an overall cost analysis. This program yielded an overall 13.11% return on investment and a 5.7 year payback period.

8 Business Plan

Simultaneous with this project, Team 09 worked on a business plan simulating the startup of a new company named World’s Strongest Can. This plan assumed that the company’s fiscal endeavors would be both successful and repeatable. A succinct summary of this report is included in the following section.

8.1 Vision and Mission Statement

8.1.1 Entrepreneur’s Vision for the Company

World’s Strongest Can’s vision is to produce Aluminum Oxynitride powder with a high level of quality while reducing the current production costs required to make this product. In addition, this company will recycle aluminum beverage cans at our facility not only to reduce production costs, but to also reduce the heavy price paid by our environment in this industrialized culture. We aim to stay at the forefront of the defense industry, while remaining open to the idea of entering other markets in which we are well suited to excel. The engineers employed with us will not only be responsible for current production, they will also research other products and markets in which we may compete in.

8.1.2 Values and Principles on Which Business Stands

World’s Strongest Can is built on the foundation of three core values; stewardship, caring, and trust. It is imperative that we as a company strive to incorporate each of these values into our everyday business. Stewardship will be achieved by recycling cans, as well as reducing energy consumption during the energy intensive processes conducted at our company. Caring and trust will also be displayed in our company not only in the way we treat our employees, but also in how we conduct business with suppliers and consumers. Products made by our company may be used
in life and death situations, and it is necessary that we provide a quality and trustworthy product.

8.2 Industry Background and Overview

The production of AlON ceramic is a new process, beginning in the recent decades. Surmet, a ceramic company founded in 1982, started to produce this ceramic once it acquired AlON Technology from Raytheon in 2002. The greatest amount of development in the industry has happened in the past couple of years. These developments have increased not only the feasibility of the process, but also decreased the cost of the production. However, the process of producing AlON powder, the material from which the ceramic is made, still costs a lot. The price of the powder in combination with the technology required to produce it keeps many companies from entering this market. This also is a product that requires extremely high purity, which the industry has traditionally defined in terms of optical properties, affordability, and strength. With the focus on these aspects, company can be competitive in the industry.

8.3 SWOT Analysis

SWOT is a type of analysis which aids in the production of a business plan, which stems from the mission vision and goals of the particular company. This analysis includes a highlight of the Strengths, Weaknesses, Opportunities and Threats to the company both internal and external.

8.3.1 Strengths

The main strength of the company is the widening of a previously monopolized market. By supplying the intermediate for the aluminum oxynitride production, more companies are now able to join the market and compete with the one and only aluminum oxynitride producer, Surmet. In addition, the company is utilizing environmentally friendly methods of production resulting in a positive public image, as well as a lower cost for production. The company is beginning
production at a reasonable annual output, resulting in substantial room for growth and expansion if the demand for the product meets the supply goals.

8.3.2 Weaknesses

While the introduction of the new market is viewed as a strength as there is no competition, it can certainly also be viewed as a weakness too. While the lack of competition is an immediate plus, the fact that there has never been competition to Surmet can possibly intimidate other companies away from purchasing our intermediate product. With zero precedents, other companies would feel like their abilities to hot press powders could be more safely used producing other products. In order to eliminate this fear, the product and the potential profit that can be gained by furthering the aluminum oxynitride production process must be stressed severely. If companies were to understand that the risks heavily outweigh the risks in this market, the demand for our intermediate product would become significantly larger.

8.3.3 Opportunities

The company has the opportunity of growth in regards to the amount of raw materials it brings in for product development. With the basis for the used beverage cans utilized as the main raw material for production, and the number of cans available used on the basis of the amount of recyclable cans available in the Grand Rapids, Michigan area, the amount of powder that the company has the potential to produce has the ability to rise as the ability to accumulate cans rises. The raw materials would be able to be increased by raising the percentage of cans accumulated within the Grand Rapids area, or even outsourcing to neighboring areas. This expansion would be further pursued once the demand for the company’s product rises due to customer acceptance and approval of the furthering of aluminum oxynitride production. World’s Strongest Can is confident
that the customer approval will be high, and therefore the demand will rise, and expansion will be inevitable.

8.3.4 Threats

The major threat to World’s Strongest Can’s operations is the lack of demand for our product. This could be a result of potential customers being too afraid, or even the large current corporation Surmet bullying potential customers out of the market. If Surmet were to lower their costs significantly, that would result in our potential customers not being able to sell the final product for a profit, based on the sale price that our company is basing for our company to make a profit. In addition to this significant threat, there is the ever-prevalent threat of other startup companies with a similar idea and business plan. Depending on the success of our company, other entrepreneurs would want to emulate the success and enter the business. In order to mitigate this threat, the company will need to patent the process, as well as continually develop new and innovative ways to produce our product in order to stay ahead of anyone trying to compete.

8.4 Target Market

World's Strongest Can’s target market is a facet of companies that contain the resources, capabilities, and desire to conduct hot isostatic pressing. With this ability, these companies will be able to take our product, the AlON powder, an intermediate in the production of AlON transparent ceramic, and actually produce it. This requirements for entry into this market is not a widespread ability, therefore the target market is rather small.

8.5 Benefit Offered

As there is only one company (Surmet) currently making the ceramic due to the difficulty of procuring aluminum oxynitride, this process will essentially grant access to a stronger, cheaper material than bulletproof glass that is also clear and lightweight. This material, once widely
available, could create a new standard in safety and general toughness. World’s Strongest Can proposes the widening of the aluminum oxynitride market by enabling various other companies the ability to enter the market through purchasing the intermediate of production. By supplying the aluminum oxynitride powder to these companies at a low price, they will be able to produce the end product and immediately enter the market competitively against Surmet. The marketability for World’s Strongest Can’s product, is the high marketability of our customer’s product.

8.6 Competitor Analysis

There are not currently many competitors to us in this industry, but the current competitor we do have has a stronghold on the entire market we wish to enter. We aim to compete with them by having lower production costs, and in turn a lower selling point.

8.7 Existing Competitors

As previously mentioned, there is only one competitor currently in this market. This competitor is a company called Surmet, based in Massachusetts, who only has one production facility. Surmet is a material solutions company who currently produces five main products, all of which are ceramics. Surmet sells the equivalent to what our company is making, ALON, at a price of $10-$15 per square inch, and produces an unspecified “tonnage” of ALON product annually. Our company plans to greatly reduce this cost while still being able to produce a comparable amount of product.

8.8 Potential Competitors

Potential competitors include the competitors that have either the capability to enter the market, and interest to enter the market, or both. A few examples of local companies with such capabilities are: Alcoa, Temper Inc. and SunRock Ceramics.
8.9  Business Plan Conclusion

After analyzing the entire market, a proposal was made to a group of investors for the actual implementation of the industrial plant. This proposal included financial calculations and estimated projections for the future of the company, and concluded with a request for a loan based upon the profitability of the proposed company.

9  Conclusion

Analyzing all of the potential processes that could be used to produce AlON revealed the most efficient and cost effect method. The most effective synthesis route was determined to be a process that first converts aluminum to aluminum oxide and aluminum nitride. These two reactants can then be converted to the desired aluminum oxynitride. It has been determined that this process is in fact feasible, since the synthesis route chosen is already used in industry. It also can be concluded that it is possible to obtain all required aluminum from recycled beverage cans due to the amount of available cans in a given area and the purity of aluminum that can be achieved through recycling. The design of this process yielded a break-even price of $11 per kg of powder, which is significantly lower than the estimated Surmet price of $58. These economics prove that this design is a feasible and realistic way to produce AlON powder at a reduced cost, allowing it to be utilized to its full potential.
Acknowledgments

There are many people responsible for contributing to the success of this project, and Team 09 would like to acknowledge them. First of all we would all like to thank our families for their unwavering love and support. We would like to especially thank Professor Jeremy Van Antwerp for consistently giving constructive critiques and feedback, supplying ideas and thoughts to further the progress of the project. And finally, we would like to thank our industrial mentor’s, Luke Martin and Bill Dykstra from Temper Inc. for supplying practical industrial expertise and critiques about our project. Without all of this support, we would not have been able to have accomplished such a successful project.
Appendix:

Table 6- Capital Cost Equations

<table>
<thead>
<tr>
<th>Number</th>
<th>Equipment</th>
<th>Capital Cost Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fired heater</td>
<td>$Cost = \exp(0.32325 + 0.766 \times \ln(Q))$</td>
</tr>
<tr>
<td>2</td>
<td>Compressor</td>
<td>$Cost = \exp(8.123 + 0.7243 \times \ln(Hp))$</td>
</tr>
</tbody>
</table>
| 3      | Pressure Vessel    | $Cost = \exp(7.0132 + 0.18255 \times \ln(W) + 0.02297 \times \ln(W)^2)$  
Where $W = \pi(D + ts)(L + 0.8D)ts \times \rho$ |
| 4      | Recycling Apparatus| $Cost = K \times (1 + fd + fp) \times Q^{0.82} \quad 2 < Q < 30 \text{ M Btu} , C \text{ is in } \$1,000$ |
| 5      | Filter             | $Cost = 3.1 \times A^{0.59} \times K, 0.5 < A < 35 \text{ sq ft}, C \text{ is in } \$1,000$ |
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   http://www.kab.org/site/PageServer?pagename=recycling_facts_and_stats


3. “CVD Processes an (Sennan, Japan Patent No. 4612045, 1986)d Equipment” Handbook of Chemical Vapor Deposition


6. (Sennan, Japan Patent No. 4612045, 1986)


12. (Kawasaki, Japan Patent No. 5,769,331, 1998)


