Title
Titania Coatings: Smog-Reducing Roof Coating

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TITANIA COATINGS: SMOG-REDUCING ROOF COATING

By

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A capstone project submitted for
Graduation with University Honors

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University Honors
University of California, Riverside

APPROVED

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Abstract

The issue of air quality has become more prominent due to the continuous production of dangerous compounds. One such compound is nitrous oxides, or NOx, which is a criteria pollutant that is produced from various sources and has adverse health effects. Current government regulations work to limit its production; however, there are a limited number of products that work to tackle the amount that already exists within the atmosphere.

The goal of Titania Coatings is to provide a simple and accessible solution to this problem. The team has developed a product that works to passively reduce ambient concentrations of NOx in the atmosphere. Our product is a spray coating that can be applied in a thin layer to any rigid outdoor surface, with rooftops being the primary surface of choice due to extended sunlight exposure with little to no disturbances. The main component of our product is nanoscale titanium dioxide, an oxidative photocatalyst that reduces NOx into solid nitrates when exposed to sunlight.

One of the team's main goals this past year was to determine the deposition velocity of NOx onto the surface of roof tiles treated with our product. Through experimentation completed at the Center of Environmental Research and Technology Atmospheric Processes Lab (CE-CERT APL), the deposition velocity was determined to be 0.084 cm/sec. Additionally, these tests showed an average reduction rate of NOx to be 25%, which shows significant implications of air quality improvement with large-scale implementation. A flux model was then created in order to quantify the effectiveness of our product. From this, it was determined that in order to reduce all ambient NOx in the Riverside basin within a 24-hour period, roughly 457,000 average home-sized roofs would need to be sprayed with our product.

Lastly, an economics study was completed for this project, with our break-even point being $0.99 cost per square foot of sprayed roof. The team decided to sell our product at a price of $1.50 per square foot of sprayed roof which would result in a net profit of $1.82 million dollars. The profit can be used to further improve air quality through a number of other avenues, such as education and technology.


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Acknowledgements

I would like to thank my team members Tom Eckel and Nina Nester, who gladly welcomed me onto the team one year ago. Throughout the past year on this team, I have learned so much from working with these two amazing and talented individuals. I thoroughly enjoyed working on this project and it would not have been as successful or rewarding of an experience without the help and dedication of my team members.

I would also like to acknowledge Dr. David Cocker for his tremendous help the team with troubleshooting and with guiding us in the right direction. The team also had the pleasure of getting another faculty member on board this year, Dr. Cesunica Ivey. We are so grateful for the time and effort that she has invested into the team over the past year and for willing to serve as the main Principal Investigator for the upcoming year.

Lastly, I would like to gratefully acknowledge Dr. Kawai Tam for all of her guidance and mentorship throughout the course of this project. I have learned and grown so much more than I ever thought I would when I first joined this team. Dr. Tam was pivotal in my progress and growth as a professional engineering student and she has thoroughly prepared me for the next step in my engineering career. I cannot thank her enough for always making herself available to help myself and the team despite her busy schedule. Dr. Tam has served as one of my role models throughout the course of time at UCR and it would not have been the same without her.

Allocation of Responsibilities

As a part of Titania Coatings, I had the pleasure of working with a great team of engineering students and the opportunity for mentorship from amazing faculty from the Department of Chemical and Environmental Engineering. As a result, this project would not have been successful without all of their help. My team members and I worked collaboratively throughout the course of the project in order to deliver our final product. Descriptions of each team member’s responsibilities are detailed below.

Tia Borja: I have been a part of the Titania Coatings team for one year. My main role in the project was assisting with fabrication of roof tiles, experimentation, and compilation of data. I also helped construct our new testing chamber during Winter quarter, which was a collaborative effort among all group members that took nearly a month to complete. In addition, I have taken responsibility for many of the administrative and design responsibilities such as helping create the team’s new logo, designing flyers for recruitment, sending email updates and managing the recruitment process. I was also responsible for the creation and maintenance of the team’s new website and am credited as the webmaster.

Nina Nester: Nina’s focus as a team member for over one and half years has been on fabricating roof tiles, researching compounds and possible additives, and preliminary experimentation. She also contributed to the construction of the chamber. Nina was responsible for contacting outside sources, such as manufactures of products required for the economics study in order to get price estimates. She also worked on the economics portion of the project, determining how much the product will cost and our yearly profits.

Tom Eckel: Tom has had a variety of responsibilities while on the Titania Coatings team, as he has been a member for two years. His main focus has been to facilitate deposition velocity testing at CE-CERT and the development of the flux model. He has been the point of contact for technical support and has also contacted vendors for purchasing supplies using grant proposal funds. He has also worked extensively on the deriving the flux model calculator for the team and has served to guide Tia and Nina through much of the calculations.

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Introduction and Background

Air pollution is a prominent issue in today's world that affects humans, animals, and the environment. People who live in urban, high population areas are particularly prone to exposure of dangerous compounds, due to high production from possible nearby industrial zones or the production from mobile sources such as cars and trucks. One compounds of particular interest is nitrous oxides, or $NO_{x,}$ which consists of nitrogen oxide (NO) and nitrogen dioxide (NO_2).

With the advent of the Environmental Protection Agency (EPA) and the Clean Air Act of 1963, pollution has been monitored and regulated to limit emissions from stationary and mobile sources. As a result, EPA data states that "between 1970 and 2017, the combined emissions of the six common pollutants (PM2.5 and PM10, SO_2, NO_x, VOCs, CO and Pb) dropped by 73 percent" [1]. However, residents of especially high populated areas can still see a brown layer of smog over the horizons of large cities, which reduces visibility. NO_x is just one compound out of a few that contribute to smog [2]. Additionally, NO_x is one of the primary causes of acid rain which damages buildings and has adversely affects marine and forest life. NO_x also has dangerous affects to humans in prolonged contact with the compound. It degrades lung function and increases the risk or bronchitis, the effect of which is amplified in children [2]. There are many ways in which NO_x negatively affects our world, which is why its ambient concentrations should be minimized. Catalytic converters in cars help to reduce the output of NO_x, but few solutions to reducing these pollutants once it is already in our atmosphere exist.

The goal of the Titania Coatings is to provide a very simple and efficient method of reducing the amount of ambient NO_x which already exists within the atmosphere. Our product is a spray coating that can be applied to any rigid outdoor surface. However, roof tops are the primary surface of choice due to the long exposure to sunlight with little to no outside interference with the surface. Our product is created by mixing three ingredients: nanoscale titanium dioxide (active photocatalyst), deionized (DI) water, and a binding agent. After a roof is sprayed with our product, a photocatalyzed reaction occurs between the active catalyst (titanium dioxide) and gaseous NO_x molecules that deposits onto the surface. The end result is the formation of solid nitrate (NO_3) molecules which reside on the surface of the coating until they are washed away with water during rainfall. Nitrate is a common compound in fertilizer, and the predicted amounts washed into soil present only a positive effect on plant growth. In areas where the estimated amount of nitrates is predicted to exceed current environmental standards, a filtration system can be installed to reduce concentrations or capture the nitrates for alternative use.

Titania Coatings hopes that with the implementation of our product, health and safety risks will be significantly lowered. Our aim is to provide a solution to the issue of high ambient NO_x concentrations that is simple and sustainable. Potential liability mitigation and reduced impact on the environment serve as prime incentives to implement our technology. A small initial cost guarantees a cleaner conscience as well as environment.

Previous Work

The Titania Coatings project began as a senior design idea and has been passed onto continuing engineering students over the course of a few years. This past year, the project has been the focus of three senior chemical engineering students, including Tom Eckel, Nina Nester, and myself. Previous iterations of the team worked on optimizing different aspects of the product. Their accomplishments included adhesion of the nanoscale titanium dioxide to various roofing substrates, optimizing the ratio of coating components to provide the greatest oxidation efficiency, proof of concept testing, and securing grant funds for further experimentation of the project.

Competitors

Nanoscale titanium dioxide has been investigated for its ability to reduce a number of dangerous compounds. There are a few products other than ours that utilize this compound for the purpose reducing NO_x specifically. One product from the United Kingdom (Competitor 1) is a roof tile that utilizes titanium dioxide in the outermost of several layers to reduce NO_x. Another similar product from the United States are smog-reducing roof shingles (Competitor 2), which also implements titanium dioxide into the product to reduce NO_x. This solution and those like it are somewhat limited in scope, as they require the rooftops of standing structures to be replaced. Competitor 1 also has no commercial equivalent for industrial rooftops such as warehouses, plants, docks, and airports, which are facilities with sources of NO_x. What makes the Titania Coatings product more effective is that the fact that our spray can be directly applied to substrates without changing existing structures. This significantly cuts down on labor cost and materials cost, which makes it a much better alternative.

Design and Experiment

During the past two quarters of senior design, the team's main goal was to create an airshed model to determine how effective our product is as well as its sustainability impact on the environment. The critical figure in being able to determine the environmental impact of our product are known as the deposition velocity value, or V_d which is expressed in units of cm/sec, which for NO and NO_2 over dry land are 0.016 cm/sec and 0.1 cm/sec, respectively [3]. This figure along with the number density (in units of molecules/cm^3, which is a function of the concentration of NO_x in the local atmosphere), the molecular flux of NO_x (in units of molecules/cm^{2}sec) out of the atmosphere as a result of the team's product can be calculated. Using this figure and the area of treated surfaces, the molecular flow rate of NO_x to treated surfaces can be modeled. For our product to demonstrate significant potential as a viable air quality treatment, a deposition velocity higher than the standard for either particle was desired.

In order to do determine the deposition velocity of NO_x, the team had to build a new testing chamber, illustrated by Figure 1 below. The previous testing chamber was constructed in a cylinder tube shape, which was not large enough nor practical for conducting tests that required the placement of roof tiles inside the chamber. Therefore, a new rectangular testing chamber was constructed. This shape limits the passage of the polluted stream to flow directly above the roof tile, assuming the tile has been cut to the full width of the chamber.

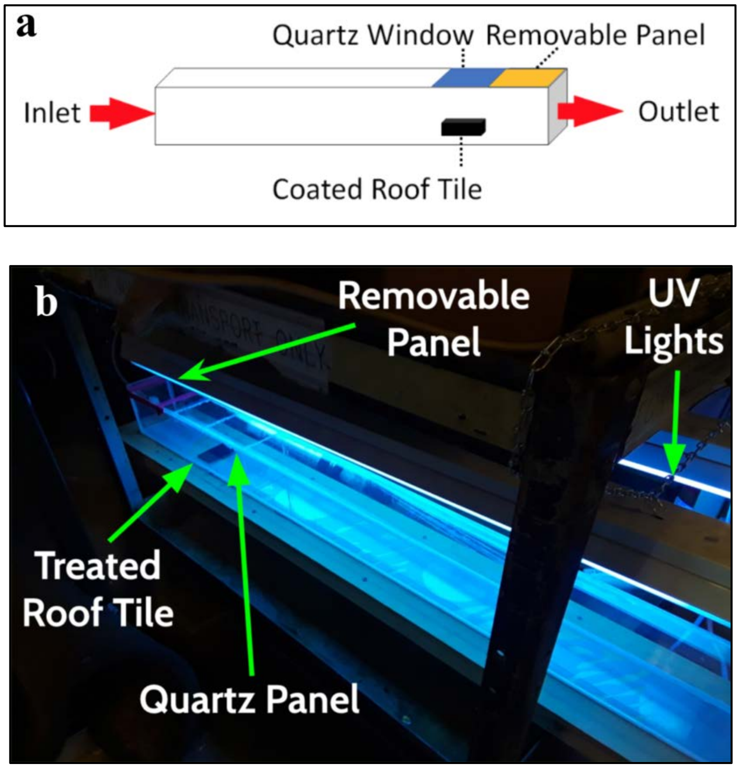


Figure 1 (a): Diagram of testing chamber, and (b) photo of chamber with UV lights turned on.

All control tests and deposition velocity tests were conducted by flowing NO and ozone (O_3) into the chamber, the inlet concentrations of which are both known and adjusted. The ozone stream reacts with the NO stream before they reach the chamber, which allows it to convert a certain portion of the NO into NO_2. The outlet concentration is then recorded using a Thermo Fisher Model 42 NO_x chemiluminescence analyzer. The outlet concentration is measured at 1-minute increments until it hits a steady-state. Then the UV lights above the chamber are switched on and the time at which it was turned on is recorded. The outlet concentration is continuously recorded until it plateaus again, indicating the NO_x in the chamber is being reduced at a steady-state. The full experimental set-up is illustrated in Figure 2 below, which includes the chamber, UV light, NO_x analyzer,

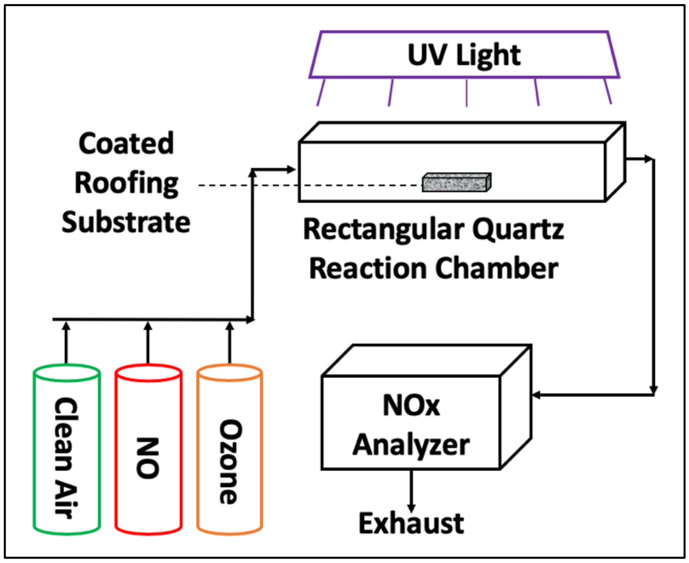


Figure 2. Current experimental design overview.

The amount of NO_x deposited is calculated from the outlet concentration which changes over time; this also is key determining the flux of the NO_x onto the surface of a roof tile. From the graph of outlet concentration with respect to time, the average reduction efficiency can also be calculated.

Results and Discussion

Control Tests

Following construction and installation of the new testing chamber at CE-CERT, control tests and deposition velocity tests began. The team first started with control experiments in order to determine how much, if any, NO_x degrades on its own or on the surface of an untreated roof tile in the presence of UV light. Our hypothesis was that the concentrations of NO_x would be unaffected by UV light alone. As shown in Figures 3a and 3b below, the results of these control experiments showed no significant decrease in NO_x concentration. This supports our hypothesis and is significant because it means that there is NO_x degradation due to UV or the substrate being used in the experiment; therefore, all pollution reduction is a direct result of the developed coating.

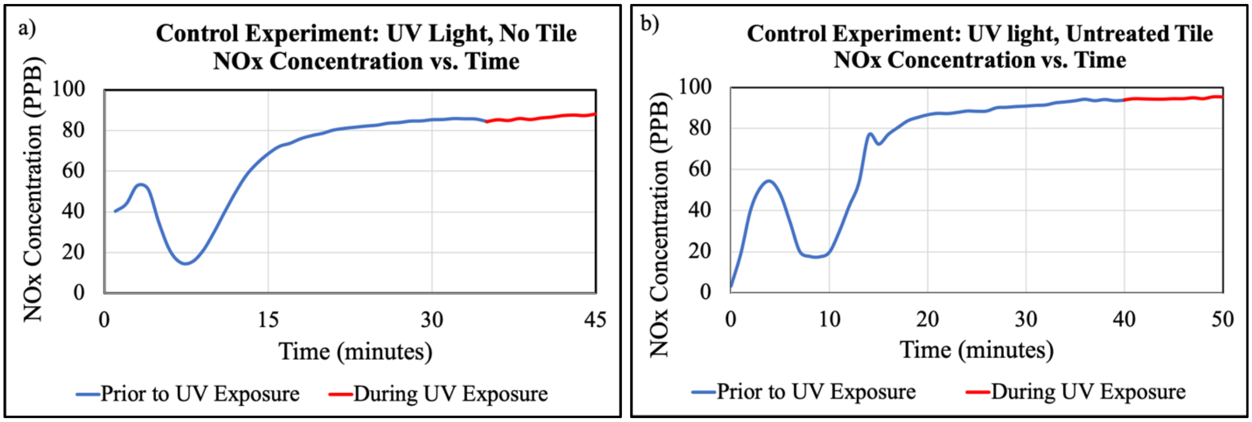


Figure 3: (a) Plot of NO_x concentration vs. time for control test for UV light and no tile, and (b) Plot of NO_x concentration vs. time for control test for UV light and untreated tile.

Deposition Velocity Tests

Following the control tests, the team was then able to begin deposition velocity experimentation. A total of three tests were conducted with the following parameters: air at 2 L/min, NO at 5.9 cc/min, 0.19 L/min, and the NO to NO_2 ratio being 10:90. The results of all three trials are shown in Figure 4 below, with the dashed lines indicating the time at which the UV lights were turned on for each experiment. From these tests the deposition velocity was determined to be 0.084 cm/sec, and the average reduction efficiency was determined to be about 25%. This reduction efficiency has implications of significant impact if the product is eventually implemented on a large-scale.

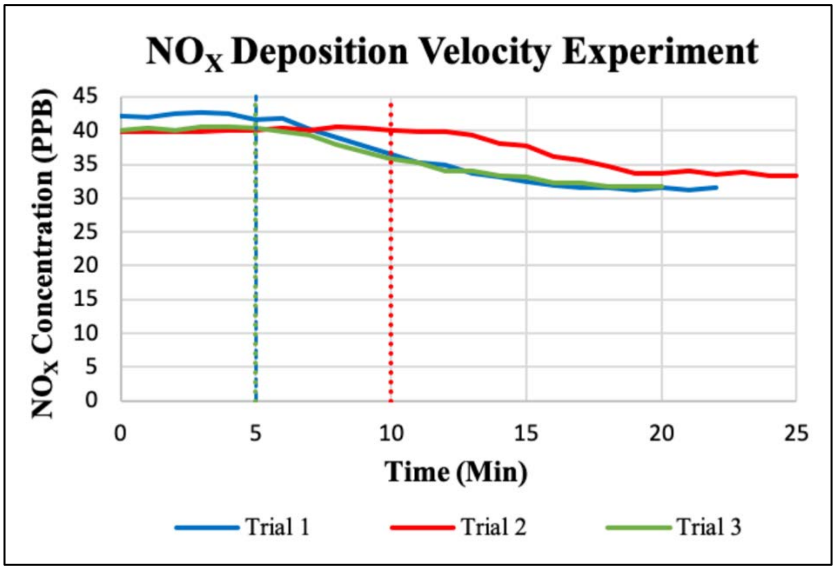


Figure 4. Plot of NO_x concentration vs. time for deposition velocity tests, with the dashed lines indicating the times at which the UV lights were turned on.

Scale-Up: Flux Model

With the calculated deposition velocity, the team was then able to start on the creation of a flux model which would allow us to quantify the effectiveness of our product. The team first started by taking a base case; we decided to take the roof top area of CE-CERT APL (the facility at which the team conducts our research) and determine how long it would take to reduce all ambient NO_x into nitrates. The roof top area was determined using the City of Riverside's geographic information system (GIS), which was accessible online. A few key assumptions were made for these calculations, which are detailed as follows: it was assumed that we were looking at a 20 meter column of ambient air with no wind speed above the treated surfaces, and that it was a well-mixed column meaning that there was a constant concentration of NO_x throughout the column.

The rooftop area of CE-CERT APL was estimated to be about 286 m^2 using GIS. With the flux model calculator, it was determined that it would take roughly 6.65 hours for our coating to oxidize all the ambient NO_x within the 20 m column above the roof into solid nitrates. This calculation gave the team a rough idea of how fast and effective our product could be when implemented on a larger scale.

After our base case test, the team then posed the question of how many average sized roofs (3000 ft^2) would have to sprayed in the entire Riverside Basin in order to oxidize all NO_x within a 20 m column into nitrates in a 24-hour period. Using the flux model, this value was calculated to be roughly 456,693 average home sized roofs. While this might seem to be a large number, this calculation gives a rough idea of how fast our product can make a significant impact on air quality within just the Riverside area, and later on within Southern California and globally.

Scale-Up: Chemical Design System

The end goal of our project is to eventually commercialize our product in order to help significantly improve air quality in high density population zones and surrounding residential areas. With this goal in mind, the team constructed the design of the full-scale chemical system. The system is quite simple and only includes a single unit process which is a continuous stirred tank reactor (CSTR). In this reactor, nanoscale titanium dioxide in powder form is added, then the binding compound is pumped into the reactor using a centrifugal pump. The reactor is continuous stirred due to the tendency for nanoscale titanium dioxide to settle with little to no agitation. After all compounds are well-mixed, the product is then sprayed onto roof tops or other outdoor surfaces using an industrial nozzle. A diagram illustrating this full design is shown in Figure 5 below.

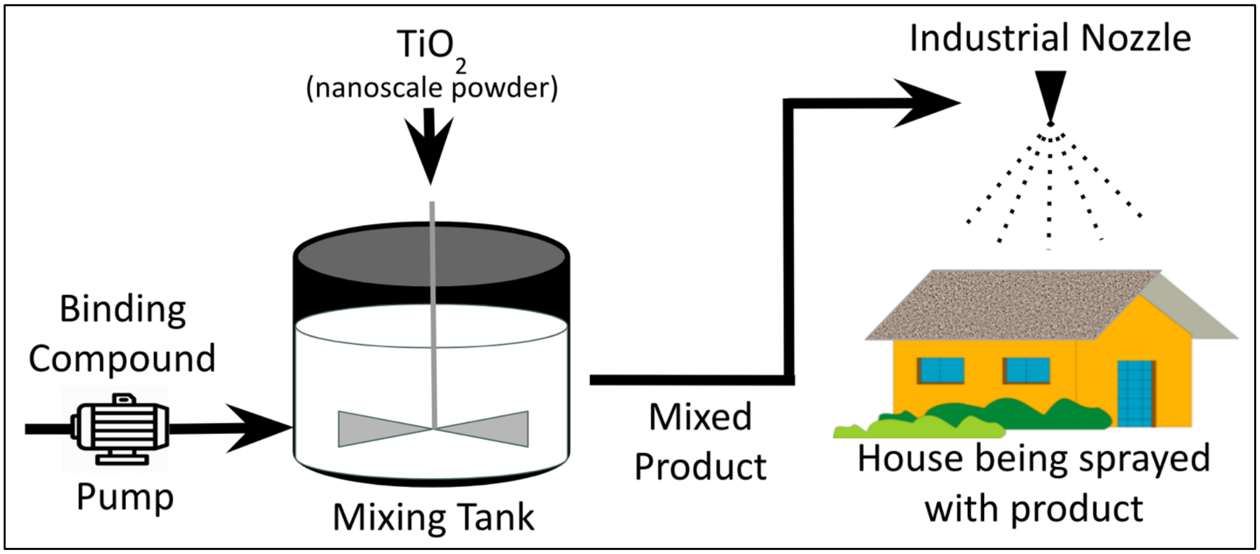


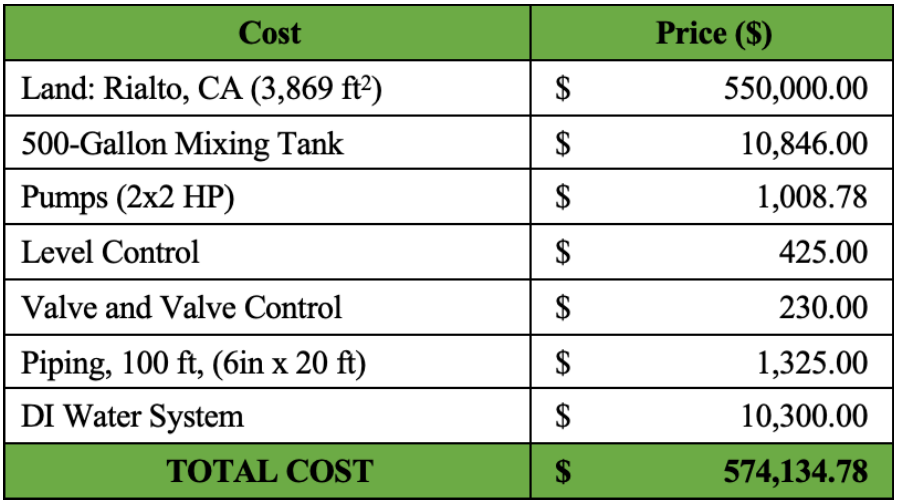
Figure 5. Diagram of full design of chemical system after commercialization and large-scale production of product.

Scale-Up: Economics

With the end goal of commercialization in mind, the team conducted an economics study for large-scale implementation of our product. In order to complete this aspect of the project, the team conducted research on materials prices and operation expenses in order to determine the breakeven price of our coating per square foot of roof tile sprayed. This breakeven value is essentially the price that we would sell our product at in order to obtain a full rate or return on investment. in other words, we would neither be making money or spending money at this price. The tables below include this information; Table 1 lists the capital expenses and their prices and Table 2 lists the yearly operation expenses of our plant.

As listed in Table 1, one of the capital expenses include land cost. For our chemical process, the team found a small warehouse of 3,869 ft^2 for the large-scale manufacturing of our product. The team chose a warehouse located in Rialto, California which is in San Bernardino County. This location was chosen because of the inexpensive land costs at a price of $550,000 and it is in direct proximity to our consumer base. An image of this location on a map is shown in Figure 6 and a photo of the warehouse itself is shown in Figure 7.

Table 1. Capital Expenses



Cost	Price ($)
Land: Rialto, CA (3,869 ft^2)	$ 550,000.00
500-Gallon Mixing Tank	$ 10,846.00
Pumps (2x2 HP)	$ 1,008.78
Level Control	$ 425.00
Valve and Valve Control	$ 230.00
Piping, 100 ft, (6in x 20 ft)	$ 1,325.00
DI Water System	$ 10,300.00
TOTAL COST	**$ 574,134.78**

Table 2. Operation Expenses

COST	PRICE ($)
Water	$ 13,949.79
Electricity	$ 9,329.88
Salaries (6 workers)	$ 132,000.00
TOTAL COST	**$ 155,279.67**

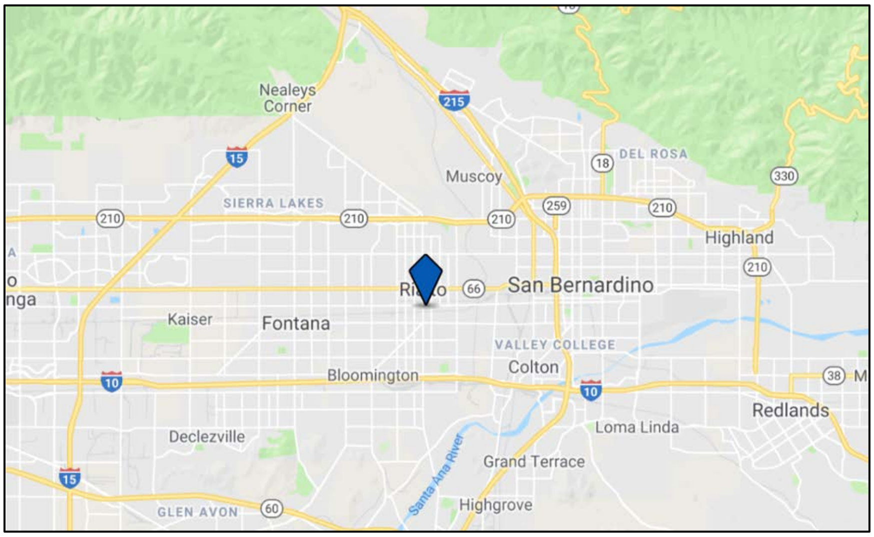


Figure 6. Map of San Bernardino County indicating the location of the warehouse.

Figure 7. Photo of the outside of the selected warehouse facility for manufacturing.

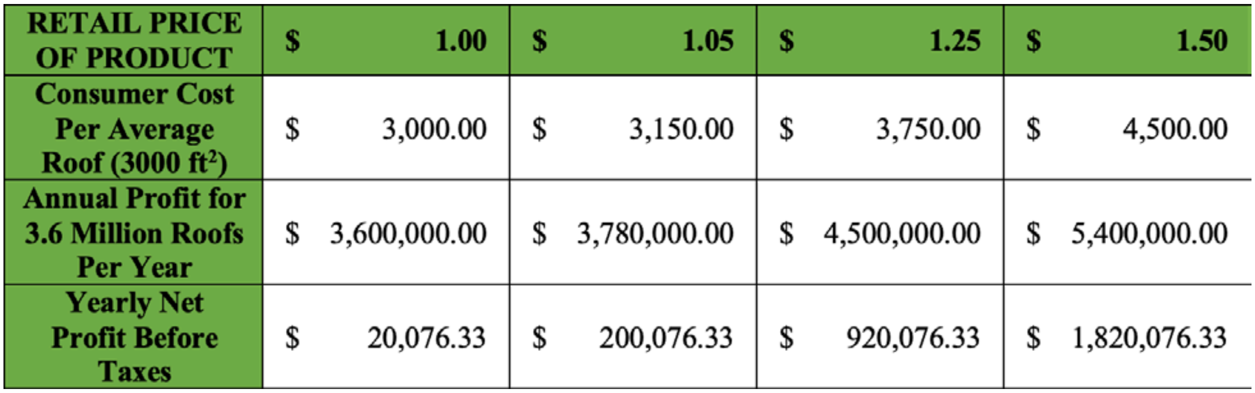
Through our economic calculations, the cost of the product to breakeven was calculated to b $0.99 per square feet, which shows that our product is not only beneficial in impacting air quality, but it can be done at a low cost.

Scale-Up: Market Share Viability

Titania Coatings aims to partner with government agencies such as EPA in implementation of our product on a large-scale. Our goal with this is to provide tax reduction benefits to owners of industrial buildings who agree to implement our product.

Currently, our main competitors are Competitor 1 from the United Kingdom with titanium dioxide roof tiles and Competitor 2 from the United States with roof shingles. Both companies do not have economics data or market prices readily available. This prompted the team to calculate our yearly profits at various price points of our product, the results of which are detailed in Table 3 below. With determination of the market prices of our competitors' products, the team will be able to set a price point which makes our product competitive to them.

Table 3. Comparison of various price points per square foot of product to observe differences in yearly net profit.



RETAIL PRICE OF PRODUCT	$ 1.00	$ 1.05	$ 1.25	$ 1.50
Consumer Cost Per Average Roof (3000 ft^2)	$ 3,000.00	$ 3,150.00	$ 3,750.00	$ 4,500.00
Annual Profit for 3.6 Million Roofs Per Year	$ 3,600,000.00	$ 3,780,000.00	$ 4,500,000.00	$ 5,400,000.00
Yearly Net Profit Before Taxes	$ 20,076.33	$ 200,076.33	$ 920,076.33	$ 1,820,076.33

Future Work

Within the last few weeks of Spring quarter, the team had to make the decision of whether or not to recruit new team members, since the current members are all seniors. The team was lucky enough to have Dr. Cesunica Ivey agree to take on next year's team as Principal Investigator, and the team proceeded with recruitment. Three new team members have been recruited for the following year, and the team's new senior design goal will be centered around the efficiency of our product in reducing another compound of significant interest called volatile organic compounds (VOCs). The current team has conducted literature research on the environmental and health impacts of VOCs, as well as the ability of titanium dioxide catalysts to reduce VOCs. Due to time constraint on behalf of the current team, a full study on VOCs was not able to be completed. However, with this new team, the current members are confident that the project will continue to grow and move a step closer to our goal of improving air quality.

Conclusion

Over the past year, the team has accomplished experimentation and calculations including a flux model, which validates the potential impact of large-scale implementation of our product. What sets our product apart from other competitor is the ease of application and lower material cost. With minimal direct competition and a short return of investment period, our product has potential as ground breaking new innovation in a new market. The Titania Coatings team has been successful in optimizing our product, providing experimental evidence as proof of effectiveness, and performing an economic analysis on our product. With these completed objectives, we hope to tackle the issue of air pollution, with NO_x as our main target. Our product provides a simple, accessible, and efficient method of reducing ambient concentration of NO_x and we ultimately hope to achieve our goal of improving air quality for the betterment of humans and the environment.

References

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[3] Seinfeld, John H. and Spyros N. Pandis. “Atmospheric Chemistry and Physics: From Air Pollution to Climate Change.” *Wiley*. 2016.

Appendix

Equations

Sample Calculations