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SCHREYER HONORS COLLEGE

DEPARTMENT OF LANDSCAPE ARCHITECTURE

SOFTENING THE EDGE: A STRATEGY TO REDUCE AIR POLLUTION IN HOUSTON’S FENCE-LINE COMMUNITIES.

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ABSTRACT

Air pollution is a reoccurring global issue that has been increasing in intensity since the beginning of the industrial revolution. Contamination of the air by particulate matter (PM) and volatile air compounds (VOCs) puts people at risk of various health issues, such as lung and cardiovascular diseases, and various types of cancers. These conditions particularly affect fence-line communities who live in close proximity to petrochemical factories and refineries, as these produce air pollutants in the process of creating their products. There is a strong correlation between the people who live in industrial locations and higher rates of chronic diseases; however, fence-line communities are often composed of minority populations of low socioeconomic means, who cannot afford to seek proper healthcare for the adverse effects of air pollutants on their health.

This thesis attempts to tackle issues of air pollution in Harris County, Texas, particularly in the area of the Houston Ship Channel. The channel houses one of the biggest petrochemical corridors in the nation, with over 400 petrochemical facilities and two of the largest four refineries in the United States. One particularly prominent polluter is Valero Refining Systems Inc, located next to the fence-line community of Manchester. The design project for this thesis proposes to reduce air pollution in the Valero Refinery through the use of bio-filters, which are systems that utilize microbes to break down air pollutants through metabolic reactions, and convert them into carbon dioxide, water vapor and organic biomass. Additionally, the project creates recreational and educational opportunities in the community of Manchester by exposing the bio-filtration process in a public space, through landscape designs that provide an aesthetic appeal to the site. This strategy presents an effective, cost-efficient solution to mitigate air pollution within specific sites in the Houston channel while creating opportunities for engagement with the communities surrounding these industries.
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Chapter 1

Introduction

Industrial landscapes have become an established component of channels and coasts, which are convenient locations for product exports and, therefore, an asset for industrial usage. However, the presence of these industries can also have detrimental effects on the ecosystems in which they function and the communities around them, many of which stem from the pollution of our environment. This thesis aims to address the contamination of air by industrial processes around the Houston Ship Channel in Harris County, Texas; a major petrochemical corridor that houses many minority communities of low socioeconomic means, who are directly exposed to harmful air contaminants in their current living conditions. A potential solution to this problem is the use of bio-filters- systems that utilize microbes to break down air pollution through metabolic reactions without the need to release them into the atmosphere. This technology presents an effective, cost-efficient strategy to mitigate air pollution within specific sites in the Houston channel, while creating opportunities for engagement with the communities surrounding these industries.

Pollution in the Petrochemical Age

Air pollution is a reoccurring global issue, which has been increasing in intensity since the beginning of the industrial revolution (Ritchie and Roser, 2017). Approximately 92% of people on Earth breathe contaminated air, which is the cause of nearly 6.5 million deaths per year (World Health Organization, 2018). Globally, air pollution is responsible for 29% of total lung cancer deaths, 17% of total acute lower respiratory infection deaths, 24% of total stroke deaths, 25% of total heart disease deaths, and 43% of total chronic obstructive pulmonary disease deaths (World Health Organization, n.d.). Most of the pollutants that cause these chronic diseases often stem from industrial processes, which cater
to our consumption of fuels and everyday synthetic products. Therefore, these worrisome statistics are predicted to increase as the world’s population grows, since bigger populations require higher amounts of manufactured resources. Worldwide, the demand for energy will increase 30% by 2040, and humans will use 71% more resources by 2050 (Population Matters, n.d.). Due to this demand, the increased production of petrochemical goods will generate higher outputs of air pollution into the environment.

Issues of air pollution in the United States are particularly prominent in coasts, riverfronts and channels, as these are sites with a historically predominant industrial use in most American cities. Waterfronts in the country became sites for commerce as early as the colonial period, when ships were the main mode of transportation of products and immigrants (Seattle Department of Planning and Design, n.d.). During the industrial revolution, these established ports became sites for resource shipping and industrial manufacturing. Waterfronts were dredged to accommodate rising ship sizes and new docking and industrial infrastructure was implemented in many cities, such as Chicago, Cincinnati, Pittsburgh, Houston, and New York (Seattle Department of Planning and Design, n.d.).

In modern times, there are still areas with prominent industrial sectors surrounding their waterfronts. Air pollution in these areas often gets overshadowed by water contamination issues, as it is harder to observe the immediate effects that harmful air particulates can have on the landscape and on human health. Contamination of our air by particulate matter (PM) and Volatile Air Compounds (VOCs) often stems from the same industrial processes that cause water pollution, which involve the burning of fossil fuels and the manufacturing of synthetic materials, such as rubber, paint and various petrochemicals (U.S. National Library of Medicine, 2017). PM is a mixture of solid particles and liquid droplets found in the air (“EPA Particulate Matter Pollution,” n.d.). These particles are generated in a variety of microscopic sizes; an average size is considered a PM$_{10}$ particle, which is 10 micrometers in size or smaller (“EPA Particulate Matter Pollution,” n.d.). PM$_{10}$ particles are breathable; however, it is the smaller types of particulate matter that present a higher threat to human health. PM$_{2.5}$ are particles with a diameter of 2.5 micrometers or less in size, which allows these particles to access human lungs and the
bloodstream (“EPA Particulate Matter Pollution,” n.d.). Most PM in the atmosphere is generated as a reaction between sulfur dioxide and nitrogen oxides- common byproducts from power plants, industries and automobiles (“EPA-Particulate Matter Pollution,” n.d.). Meanwhile, VOCs include the majority of carbon compounds that can generate an atmospheric photochemical reaction (“Technical Overview of Volatile Air Compounds,” n.d.). These particulates are recognized for their ability to easily become vapors or gases, as they can evaporate under standard indoor atmospheric conditions of temperature and pressure (“Technical Overview of Volatile Air Compounds,” n.d.). The gases can originate from the burning of fossil fuels and the production of various synthetic items, such as paints, thinners, adhesives, air refreshers, pesticides- among others (U.S. National Library of Medicine, 2017).

Toxic air pollutants that fall into these two categories have a negative impact in people’s health nationwide. However, issues of industrial contamination seem inevitable in an age where humans have become dependable on fossil fuels and petrochemical products to go about their daily lifestyles. In their book, ‘Petrochemical America,’ photographer Richard Misrach and Landscape Architect Kate Orff depict an example of this paradox through images of Louisiana’s petrochemical landscape, famously recognized as ‘Cancer Alley’. Images such as Figure 1.1 depict a compelling and insightful narrative about the harmful effects of petrochemical production in the small communities adjacent to this 150-mile corridor, between New Orleans and the Baton Rouge (Misrach and Orff, 2012).

Communities around industrial areas, such as the one depicted in Figure 1.1, are termed fence-line communities, as they are often located directly in the border of major industrial complexes (Air Alliance Houston, n.d.). These neighborhoods are often composed of minority populations of low-socioeconomic means, who do not have the resources or income to seek appropriate healthcare for the pollutants to which they are exposed. Misrach and Orff use as an example the community of Alsen, Louisiana, where over 50% of the population is African American and 26.1% of the population lives under the poverty level (U.S. Census Bureau, n.d.). This heavily industrial fence-line community is surrounded by big corporations since the 1950’s, such as Union Tank Car, Foster Grant, Exxon, Deltech
and Georgia Pacific (Misrach and Orff, 2012). The area produces over 1.6 million barrels of crude oil daily, 2.7 trillion cubic feet of natural gas yearly, and a range of different petrochemical products that include coke, polyethylene and bleached paper (Misrach and Orff, 2012). As a result, the area is also one of the most contaminated in the nation, producing a variety of harmful air pollutants that are shown in Figure 1.2. This region also has higher rates of heart disease, cerebrovascular disease, lung cancer, breast cancer and all-cause mortality than the national average, all surpassing their respective national rates by a minimum of 15% (Institute for Health Metrics and Evaluation, 2016).

Figure 1.1. An image of Richard Misrach’s exhibit, “Revisiting the South: Richard Misrach’s Cancer Alley”, depicting the Holy Rosary Cemetery with Dow Chemical Corporation’s Union Carbide Complex in the background. Taft, Louisiana, 1998. Source: Misrach, n.d.
Figure 1.2. Map depicting the different pollutants found in Louisiana’s petrochemical Corridor. Source: Misrach and Orff, 2012.

Similar to Louisiana’s petrochemical sector, Harris County in the state of Texas (depicted in Figure 1.3) is also home to one of the biggest petrochemical corridors in the entire country, and possesses a high number of fence-line communities. This is due to the presence of Houston, which is currently the top exporting metropolitan area in the nation with $95.7 billion worth of products and energy services shipped in 2017 (Greater Houston Partnership, 2018). Its leading exports include chemicals, refined products, oil and gas extraction, and industrial machinery, the majority of which are manufactured in the Houston Ship Channel, located in Buffalo Bayou. This 50-mile long strip of industry houses over 400 chemical manufacturing facilities and two of the four largest refineries in the United States (Bethel et al., 2005).

Within Houston’s petrochemical corridor, air pollution emissions are one of the highest in the nation. Just in 2018, industries in the county have reported more than 150 pollution releases that exceed the state’s emission permits, which add up to over 1.5 million pounds of harmful gases released (Nelson, 2018). Often, the fence-line communities who live in a close perimeter to the petrochemical corridor get the most exposure to these harmful gases, yet they have low socioeconomic means to seek healthcare. Some areas within the ship channel are the poorest in the city, with average median household incomes of
$13,395, as compared to the median household income of $47,010 for Houston as a whole (“Houston Quick Facts-United States Census Bureau,” n.d.). Additionally, many communities around the channel have some of the highest densities of minority populations in Harris County.

Communities in east Harris, such as Pasadena (shown Figure 1.3), are composed of almost 80% Hispanics, with population densities of approximately 3,621.86 people per square mile (Zip Atlas, 2017). This is relevant because on average, 29% are foreign born and have poor English proficiency, which limits their understanding about air contamination issues in their own communities (“Houston Quick Facts-United States Census Bureau,” n.d). Additionally, this area has the highest number of people uninsured from all the census tracts in the county, with 28.7% of the population lacking health insurance. Constant exposure to harmful chemicals and a lack of socioeconomic means makes the population of east Houston vulnerable to a variety of chronic health effects. For example, an assessment along the Houston
Ship Channel found that fence-line communities with 25% or more people living under the poverty line are 4-10 times more likely to develop cancer (Linder et al, 2007). Within east Houston, that represents approximately 20.3% of the population (“Houston Quick Facts-United States Census Bureau,” n.d).

As the demand for petrochemical products and fuel continues to increase within Harris County and nation-wide, the presence of industrial corridors such as the one in the Houston Ship Channel seems unlikely to disappear in the upcoming decades. Recognizing this fact, and the fact that local communities will continue to live near these areas and be affected by harmful air releases, this thesis attempts to reach a compromise which enables both, factories and people, to co-exist in the same space while reducing the health risks to which people are exposed. The project proposes a landscape-based strategy to reduce some of the air pollution levels near one of the most known fence-line communities in Houston- the neighborhood of Manchester, located adjacent to Houston’s Valero Oil Refinery. In order to accomplish this goal, the thesis proposes the usage of bio-filters, which can absorb Valero’s air releases before they are discharged into the environment and decompose these substances in a method that is safe for the community. The thesis also proposes the use of the bio-filter area as a public park for Manchester’s residents, where they can observe first-hand the benefits of bio-filters for their community and obtain more public space.

The subsequent chapters of this thesis first analyze the history of the Houston Ship Channel as a site for international commerce and petrochemical production, and how this history of industrial use has generated large amounts of pollution in the area. Additionally, the chapters will also discuss the correlation between race, income levels and vulnerability to chronic diseases due to air pollution exposure, as well as analyzing existing technologies used to mitigate pollution of particulate matter and VOC’s in an industrial context. Finally, the thesis concludes by proposing a landscape design centered around the selected pollution-cleaning method, bio-filtration, and explains in detail the design concept, maintenance, and possible future developments of the project.
Chapter 2

Houston’s Ship Channel and Petrochemical Corridor

To understand the sources of air pollution in the city of Houston, it is important to understand the history of the Houston Ship Channel as a prime site for international commerce and petrochemical compounds production. This chapter summarizes the pivotal events in the history of Harris County that led to its current prominence in the petrochemical sector, which are also summarized at the end of the chapter in Figure 2.7. Additionally, the chapter introduces air quality issues in the area due to the petrochemical sector, and the historical initiatives the city of Houston has taken to improve air quality conditions on site.

History of the Houston Ship Channel

The Houston Ship channel, shown in Figure 2.1, played a pivotal role in the creation and expansion of the city, and is currently one of the most used waterways in the United States (Sibley, 2010). The origins of the channel come from Buffalo Bayou, which resides approximately 30 miles east from the city of Houston and connects the interior of the state of Texas to the gulf (Sibley, 2010). Due to the convenient location of the Bayou for a strategic commercial point, the community of Houston was created by the brothers John Kirby and Augustus Chapman Allen at the head of the stream’s navigable section in 1836 (Sibley, 2010). The original plan and illustration of the city is displayed on Figure 2.2. Buffalo Bayou served as a connection for cotton planters to transport their products from Houston into Galveston Bay, which was at the time the best port in Texas, and the port of Houston was officially established in January 29th of 1842 (Sibley, 2010).
During the 1850’s, disputes between Houston merchants in the port and the Galveston Wharf Company, which controlled the Galveston harbor, led the merchants to start attempts to reach the sea without going through Galveston (Sibley, 2010). These efforts continued through several years, until the Buffalo Bayou Ship Channel Company was established in 1869 to turn Houston into a delivery port (Sibley, 2010). Charles Morgan bought the company in 1874, and
dredged a channel from Galveston Bay to present day Clinton (shown in Figure 2.3) during the first two years after the purchase (Sibley, 2010). Morgan abandoned the route in 1883, shifting his focus from ships to railroads, but the United States government purchased the dredged channel in 1890 (Sibley, 2010). The channel was further dredged in order to create a more functional navigation system, and was officially inaugurated in September 7, 1914 (Sibley, 2010). The first shipment taken directly from the port to a foreign market sailed five years later, and the Houston port became the national leading exporter of cotton within the decade (Sibley, 2010). Additionally, a major oil discovery happened in January 10, 1901, in a field called Spindleop near the upper Gulf coast (shown in Figure 2.4) (Texas Almanac, n.d.). This discovery prompted an unprecedented growth in the petroleum industry within the state, increasing the amount of barrels produced from 836,039 in 1900 to 4,393,658 in 1901 (Texas Almanac, n.d.). The industry’s growth also had a direct impact in the industrialization within the Houston Ship Channel’s waterfront, as more oil refineries settled in the area due to its convenient location for exports. By 1930, nine oil refineries were located in the Houston port (Sibley, 2010); this number would continue to increase as Exxon Mobil, then known as Humble Oil & Gas Co., found oil in the nearby town of Tomball in 1933 (Hlavaty, 2017).
A major step in the emergence of Houston’s petrochemical industry occurred during World War II, due to an increased demand in synthetic rubber, chemicals and explosives (Texas State Historical Association, 2010). The war suspended normal shipping schedules in the port, but the need for petroleum products increased the presence of industries along the waterway. It is also interesting to note that fence-line communities were already present in the area, as shown in historical maps such as the one in Figure 2.5. This map from 1942 displays housing blocks around the communities of Manchester, Magnolia, and Galena Park, which are fence-line communities that still exist in the Houston Ship Channel.

During this period, industries around the ship utilized compounds such as ethane, ethylene, butane, butylene, propane and propylene to construct their products, derived from
natural gas or oil (Ryan, 2010). There was also a high usage of benzene, toluene and xylene, which are produced exclusively from oil (Ryan, 2010). More than $750 million was invested in industrial plants in the state within the decade of 1939 to 1949 in order to manufacture these products to sustain war efforts (Ryan, 2010). Moreover, the population of Harris County began to increase as the demand for petroleum and petrochemical industries grew. The census of 1930 reported that the county’s population was over five times larger than the one in 1900, with an increase of 295,542 inhabitants (Texas Association of Counties, n.d.). This increase made Houston the most populous city in Texas. At the time, Houston was composed of 78.3% whites and 21.7% African Americans; although the population of Hispanics in Houston during this year is unclear, as the census only started recording Hispanic populations beginning in the 1970s (Gibson and Jung, 2005). Historical records suggest that the population of African Americans in the 1930s concentrated in three main areas of Houston: the third, fourth and fifth wards, shown in Figure 2.6 (Kaplan, 1981). Between 1940 and 1970, the African American population in Houston increased from 21.4% to 25.7%—this increase was predominantly due to migration of African Americans from rural areas in Texas and Louisiana, many of whom initially settled in the three previously mentioned wards (Kaplan, 1981). The rise of African Americans in this area also coincided with the migration of white residents from central Houston into the outer suburbs of the Bray’s Bayou area, located in southwest Houston (Kaplan, 1981). Such population changes suggest it was during this period that fence-line communities along the channel began to shift, from predominantly white to predominantly African American, and possibly Hispanic.

Entering the 1960’s, the population boom continued. Harris County had 1,243,158 inhabitants, and Houston was now one of the largest cities in the United States (Texas Association of Counties, n.d.). At the same time, there were 200 petrochemical plants in Texas
producing compounds such as ethylene, propylene, butadiene, benzene, isoprene, and xylene (Texas State Historical Association, 2010). By 1969, Texas was supplying 40 percent of all basic petrochemicals produced in the United States (Texas State Historical Association, 2010). During the following year, Texas also produced 80 percent of the country’s synthetic rubber (Ryan, 2010).

It was during this heavy industrial period that pollution in the Houston Ship Channel started to become more apparent. The Clean Air Act was established in 1970 to address pollution problems at a national level, and its passing prompted many local governments to comply with the new federal regulations on pollution discharge (Environmental Protection Agency, n.d.). However, the chemical industry was producing 3.9 million tons of solid waste, and Texas ranked sixth in the nation in yearly discharge of chemical waste (Texas State Historical Association, 2010). Within the city of Houston, the Bureau of Pollution Control Prevention established an air pollution control program in 1967 to implement pollution reduction measures in high-risk sites (Houston Health Department, n.d.).

A similar pollution control program for water followed in 1973 (Houston Health Department, n.d.), but the programs were not able to reduce many of the hazardous emissions significantly within the decade. In 1984, petrochemical companies along the channel such as DuPont, Texaco and Dow, were forced to settle lawsuits charging them with the release of toxic carcinogenic gases, which affected plant employees and residents in the nearby communities (Texas State Historical Association, 2010). Moreover, the U.S. Environmental Protection Agency identified 14 disposal sites in the state that presented potential environmental hazards (Texas State Historical Association, 2010). Accidents involving toxic gas releases continued in 1987, when the Marathon Corporation’s refinery in Texas City, close to the Houston Ship
Channel, released a highly toxic gas that forced 3,000 people to evacuate the area (Texas State Historical Association, 2010).

Figure 2.5. Historical Map that displays Houston Streets in 1942. The map points out the location of housing blocks, housing, schools and churches adjacent to industries in the channel. Source: “Park Place, Texas,” 1946.
The city of Houston has attempted in recent years to decrease the overall amount of pollution being produced from point and non-point emitters as a whole, as well as address specific pollutants known for being severely hazardous to human health. These initiatives attracted more attention after a released report from the American Lung Association in 2000, identifying the most polluted cities in the United States, where Houston ranked fifth in the nation behind only Los Angeles, Bakersfield, Fresno and Visalia-Tulare-Porterville in California (American Lung Association, 2018). In 2007, the city released a voluntary plan that identified the major sources of benzene air pollution, most of which were industries around the Houston Ship Channel, and proposed a plan to reduce their emissions over a five year period (City of
Houston Mayor’s Office of Environmental Programming, 2007). Additionally, Houston is the city with the most air monitoring sites in the country that track the levels of pollutants listed under the Clean Air Act (Greater Houston Partnership, n.d.). However, pollution levels of individual point sources remain high in the present day. According to Environment Texas, an organization that filed lawsuits successfully against Chevron Phillips and Shell Oil for illegal pollution emissions, petrochemical industries in Houston violated pollution emission laws at least 405 times in 2015 (Environment Texas, n.d.). This included releasing five million pounds of compounds, some of which have been linked to asthma and cancer (Environment Texas, n.d.). The release of these chemicals is bound to affect an increasing amount of people as the population and the petrochemical industry in Harris County both continue to grow. Houston is projected to have a population of 2.54 to 2.7 million inhabitants by 2025, surpassing Chicago as the third largest city in the nation (Business Insider, 2015). In order to create a healthy living environment to sustain such an amount of people, it is necessary to understand the correlation between the presence of petrochemical facilities and the health effects they can have on the communities that surround them, especially communities of color with low socioeconomic means.
Houston is established by brothers John Kirby and Augustus Chapman Allen near Buffalo Bayou.

The port is dredged from the Galveston Bay to present day Clinton.

The discovery of Spindletop causes a rapid growth of the Texas petroleum industry.

The port of Houston is officially established.

Texas supplies 40 percent of all basic petrochemicals produced in the United States.

Clean Air Act is passed.

DuPont, Exxon and Dow are forced to settle lawsuits charging them with the release of toxic, cancer-causing gases, which affected plant employees and residents in the nearby communities.

Harris County release report identifying main sources of Benzene pollution and creates 5 year emissions reduction plan.

Population of Harris County by Decade

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<tr>
<td>2010</td>
<td>07'</td>
</tr>
<tr>
<td>2020</td>
<td>07'</td>
</tr>
</tbody>
</table>

Figure 2.7. Timeline of the Houston Ship Channel. Original Image Sources: (Burke, 2018), (Morgan, n.d.), (Davenport, n.d.), (UMOCA, n.d.).
Chapter 3

Correlation between Air Pollution and Health Risks in the Minority Populations of Houston.

The history of Houston’s ship channel as a major commercial and industrial sector has greatly contributed to its current challenges regarding air quality. Rapid growth of the petroleum industry began throughout Texas in 1901 with the discovery of the Sprindletop oil field, which prompted the creation of oil refineries along the channel. Moreover, the petrochemical industry prospered greatly at the beginning of World War 2, when the need for rubber, explosives and other synthetic products encouraged the surge of new industries in Houston. After the establishment of the Clean Air Act in 1970, Houston has attempted to reduce their emissions through pollution control plans for specific VOCs. However, industries along the refinery continue to violate pollution emission laws to this day. These emissions are harmful to the communities living adjacent to the channel’s industries, and cause a disproportionate amount of chronic health problems in this area as compared to the rest of Houston. This chapter presents evidence of the correlation between air pollution along the Houston Ship Channel and the high prevalence of several chronic diseases, such as diabetes, asthma and different types of cancers. Additionally, it discusses the exposure of vulnerable, low-income minority communities to these hazards due to their close proximity to the channel.
Air Pollution and Disease Prevalence

Due to the previously discussed history of Houston’s ship channel as a major global commerce and petrochemical production site, the county contributes some of the highest emissions of air pollution in the state of Texas. Table 3.1 displays the percentage of air pollution particles released in Harris county, compared to the 17 surrounding counties of the Texas Southeast Region (Figure 3.1). The table illustrates that Harris County contributes over half of the tons of PM emitted daily for a wide range of aerodynamic diameters (2.5 micrometer or less, 10 micrometer or less, and between 2.5-10 micrometers) (Lurmann et al., 1999). These types of particulates are especially significant when it comes to air pollution, as their small size allows them to remain in the atmosphere for longer periods and be transported over long distances (World Health Organization, n.d.). PM$_{2.5}$ is known to be particularly harmful, as it can lead to a variety of cardiovascular problems (heart attacks, strokes, congestive heart failure, and a reduced blood supply), as well as increasing the risk of autism and asthma in children while inhibiting their lung development (World Health Organization, n.d.). Additionally, the data indicate that Harris County contributes a significant amount of Sulphur Oxides (SO$_x$) and Ammonia (NH$_3$), two compounds often associated with combustion of ship fuels and production of plastic products, rubber and petrochemicals (Wankhede, 2017; World Health Organization, n.d.).

Figure 3.1. Eighteen County Domain in the Southeast Texas Region.
Estimate Releases of Different Pollutants in the Southeast Coastal Texas Region

<table>
<thead>
<tr>
<th>Location</th>
<th>SO$_x$</th>
<th>PM$_{2.5}$</th>
<th>PM$_{10}$</th>
<th>PM$_{2.5-10}$</th>
<th>NH$_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 Counties within Region</td>
<td>677</td>
<td>1586</td>
<td>400</td>
<td>1186</td>
<td>71</td>
</tr>
<tr>
<td>Harris County Only</td>
<td>217</td>
<td>867</td>
<td>224</td>
<td>643</td>
<td>19</td>
</tr>
<tr>
<td>Harris County Percent of Total</td>
<td>32%</td>
<td>55%</td>
<td>56%</td>
<td>54%</td>
<td>27%</td>
</tr>
</tbody>
</table>

Table 3.1. Total estimate releases of SO, PM2.5, PM10, PM2.5-10 and NH3 in tons per day within Harris County, as compared to the 18-county domain of the Houston Health Assessment. Data Source: Lurmann et al., 1999.

Moreover, the abundance of industries within the ship channel also generates a variety of other equally harmful pollutants. Houston Mayor Bill White created a special task force in 2005 dedicated to identifying and prioritizing high-risk air pollutants within Harris county. The study identified 176 air pollutants present within the county, and created five categories based on the risk that each pollutant presented towards human health. The first category, labeled as the definite risk category, was defined by the task force as pollutants with, “compelling and convincing evidence [that the substances] represent significant risk to the general population or vulnerable subgroups at current ambient concentrations” (Bethel et al., pp. 6, 2005). The 12 pollutants under this category included ozone, fine particulate matter (PM2.5), diesel particulate matter, 1-3 butadiene, chromium VI, benzene, ethylene dibromide, acrylonitrile, formaldehyde, acrolein, chlorine and hexamethylene disocyanate (Bethel et al., 2005). As shown in Table 3.2, only the last three substances on the list are not considered carcinogens, and only diesel particulate matter does not originate from a point source in Harris County. Moreover, the task force also identified nine probable risk pollutants, which are toxins with- “substantial corroborating evidence that [they may] represent a significant risk under the right conditions” (Bethel et al., 2005, p.6). This
separate category included vinyl chloride, acetaldehyde, ethylene dichloride, naphthalene, arsenic compounds, carbon tetrachloride, ethylene oxide and 1,1,2,2-tetrachloroethane, all of which are carcinogens; as well as acrylic acid, a non-carcinogen with chronic respiratory effects (Bethel et al., 2005).

### Definite Risk Pollutants’ Health Effects and Sources

**Table 3.2. Definite Risk Category Pollutants from the ‘Mayor’s Task Force on the Health Effects of Air Pollution’ assessment in Harris County. Data Source: Bethel et al., 2006.**

<table>
<thead>
<tr>
<th>Air Pollutant</th>
<th>Health Effects</th>
<th>Emissions Source</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Carcinogen</td>
<td>Chronic Effects</td>
</tr>
<tr>
<td>Ozone</td>
<td>Yes</td>
<td>R, C, I</td>
</tr>
<tr>
<td>Fine PM_{2.5}</td>
<td>Yes</td>
<td>R, C</td>
</tr>
<tr>
<td>Diesel PM</td>
<td>Yes</td>
<td>R</td>
</tr>
<tr>
<td>1,3- Butadiene</td>
<td>Yes</td>
<td>F</td>
</tr>
<tr>
<td>Chromium VI</td>
<td>Yes</td>
<td>R</td>
</tr>
<tr>
<td>Benzene</td>
<td>Yes</td>
<td>I</td>
</tr>
<tr>
<td>Ethylene Dibromide</td>
<td>Yes</td>
<td>M</td>
</tr>
<tr>
<td>Acrylonitrile</td>
<td>Yes</td>
<td>R</td>
</tr>
<tr>
<td>Formaldehyde</td>
<td>Yes</td>
<td>R, E</td>
</tr>
<tr>
<td>Acrolein</td>
<td>No</td>
<td>R</td>
</tr>
<tr>
<td>Chlorine</td>
<td>No</td>
<td>R</td>
</tr>
<tr>
<td>Hexamethylene Diisocyanate</td>
<td>No</td>
<td>R</td>
</tr>
</tbody>
</table>

**Legend:**
- R - Respiratory
- C - Cardiovascular
- I - Immune
- F - Female Reproductive
- M - Male Reproductive
- E - Eyes

Some of the pollutants included in these two lists are proven to be particularly harmful for human health. A study within Harris County found a strong correlation between the presence of benzene and 1,3-butadiene and the occurrence of childhood leukemia (Whitworth et al., 2008). According to the research, tracts with the highest levels of benzene in the air had higher occurrences of all leukemia and acute myeloid leukemia; as well as 1.24 times the rate of acute lymphocytic leukemia, as places with low benzene levels (Whitworth et al., 2008). The study also notes two separate research studies that supported their results. In the case of 1,3-butadiene, the study found significantly higher rates of all leukemia within
the census tracts with the highest concentrations of this pollutant, as well as a 32% and a 68% higher rate of acute myeloid leukemia and acute lymphocytic leukemia, respectively (Whitworth et al., 2008).

A separate study found a similar positive correlation between high concentration of Xylene in the channel and high lung cancer mortality rates during the sixties, a time when pollution regulations had not yet been implemented effectively (Walker et al., 1980). Moreover, a separate study found a correlation between exposure to benzene and PM$_{2.5}$ particulates during pregnancy and the risk of birth defects on the children, such as coarctation of the aorta and congenital heart defects (Tanner et al. 2015). All these studies indicate that there is a clear correlation between high ambient air levels of harmful pollutants and the occurrence of a variety of health problems, which holds particularly true within the communities of north and east Houston, adjacent to the Houston Ship Channel. Figure 3.1 displays such correlation, as it overlays the levels of prevalence of asthma and cancer within Harris county to the concentration levels of particulate matter. It is also important to note that these similar patterns also correlate with areas in the county where the least amount of people have health insurance.

These correlations are of serious concern, as areas with the highest concentrations of air pollution also coincide with high poverty areas, as shown in Figure 3.2, which tend to be predominantly composed of the African American and Hispanic populations of Harris County. Therefore, the location of these point sources of pollution can be seen as an environmental justice issue, where the people being most affected by the negative impacts of air pollution are the minority communities adjacent to these factories, who in most cases cannot afford health insurance or medical treatments. This correlation was also noted in some studies, which observed that the neighborhoods with the highest percentage of Hispanic populations are six times as likely to be in high-risk areas for cancer prevalence. (Linder et al., 2008). As noted in Rice University’s Annual demographics survey of Harris County, only 6.5% of participants indicated that the air quality of their neighborhood was excellent. In contrast, 24.5% indicated it was poor, while 43% indicated it was fair (Kinder Institute of Urban Research, 2018). This issue should be of upmost concern to the city of Houston and Harris County as a whole, as air pollution continues to be a
health hazard for its population. The following chapter will discuss methods that could potentially reduce air pollution in point source location of Harris County through landscape interventions.
Figure 3.3. Percentage of Poverty in Harris County as compared to percentages of African American and Hispanic Populations. Source: “HACHE Maps,” n.d.; “Houston’s Disparity Atlas”, 2016.
Chapter 4

Analysis of Design Proposals that Attempt to Absorb Air Pollution

Various projects around the world have aimed to tackle air quality issues by identifying processes that break down pollution particles and implementing those processes in design. In order to determine the most efficient method for minimizing air pollution in east Houston, it is necessary to understand and evaluate the existing projects that implement these processes, and identify their strengths and weaknesses in relation to the Houston context. As there are a variety of methods that have been historically implemented, this chapter first examines the traditional methods used to absorb and break down pollution in industrial sites or urban areas, and then examines how these have been applied in modern landscape design. Subsequently, the chapter goes over more innovative methods of pollution absorption and their implementation in design. Within these categories, the evaluation takes into account the effectiveness of each method in removing air pollutants that are largely present in Houston’s petrochemical corridor. These particulates include VOCs commonly produced in petrochemical facilities and refineries, such as hydrocarbons (mainly benzene, toluene and xylene), aldehydes (mainly formaldehyde and acetaldehyde), inorganic compounds (mainly ammonia, cyanide and sulfides) and fine particulate matter. Additionally, each category is evaluated in terms of their dependability over Houston’s wind patterns to be successful in capturing air particulates, which are shown in Figure 5.1. These patterns indicate that particulates are blown towards the east for most of the year, and wind-dependent designs will have to adapt to these patterns or implement fans to attract pollution. Finally, the chapter also considers the possible existence of large implementation and maintenance costs, and the aesthetic value they contribute to public spaces.
Figure 4.1. Wind Patterns in Houston during 2017 for every three month period. Source: NRCS National Water and Climate Center, 2017.
Traditional Pollution Cleaning Methods: Thermal and Catalytic Control Units

Thermal and catalytic incinerators are two traditional methods for disposal of VOCs. Both incinerator systems consist of combustion chambers, where the waste of industrial processes is released to be burned or to react with other substances, depending on the specific VOCs the waste gas contains (Vaart et al., 2012). Both types of combustion units require an outside fuel, such as natural gas, in order to operate, as the process requires high temperatures for combustion of the waste gases (Vaart et al., 2012). In this process, the catalytic combustion unit is more efficient than the thermal unit, as it uses metals as catalysts to increase the rate of combustion reaction, therefore lowering the required temperature for combustion (Vaart et al., 2012).

The capacity of catalytic and thermal control units to degrade/combust the targeted pollutants is moderate to efficient. The systems have the capability to achieve 25-99% removal efficiency for PM$_{10}$ in point source facilities (“Air Pollution Control Technology Fact Sheet,” n.d.). However, this is only achieved through the newest control unit technologies, as traditional units were clogged by particulate matter and prevented the unit from oxidizing pollutants (“Air Pollution Control Technology Fact Sheet,” n.d.). A downside to this aspect is that new catalyst technologies are made of platinum, which makes them expensive to construct and to replace during maintenance (certain types of metal catalysts can cost approximately $600 to $800 a cubic foot) (The Clean Air Technology Center, 2003). In terms of the targeted VOC’s, removal efficiency of the control units depends on the reactor temperatures required for combustion reactions to take place. Table 4.1. displays some of the required temperatures for a 99% removal of a variety of VOC’s, including some of the pollutants present in the Houston Ship Channel. Average unit temperatures are between 1100-1200 degrees Fahrenheit, which makes the combustion of
VOC’s feasible; however, these efficiencies are still achieved through the more expensive control units, and still require an auxiliary fuel.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Temperature (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>acrylonitrile</td>
<td>1,344</td>
</tr>
<tr>
<td>allyl chloride</td>
<td>1,276</td>
</tr>
<tr>
<td>benzene</td>
<td>1,350</td>
</tr>
<tr>
<td>chlorobenzene</td>
<td>1,407</td>
</tr>
<tr>
<td>1,2-dichloroethane</td>
<td>1,368</td>
</tr>
<tr>
<td>methyl chloride</td>
<td>1,596</td>
</tr>
<tr>
<td>toluene</td>
<td>1,341</td>
</tr>
<tr>
<td>vinyl chloride</td>
<td>1,369</td>
</tr>
</tbody>
</table>

Table 4.1. Temperatures Required for a 99% Removal Efficiency in Thermal and Catalytic Control Units. Data Source: “Air Pollution Control Technology Fact Sheet,” n.d.

Both the thermal and the catalytic control units are connected directly into the point source piping system, which prevents them from being dependent in Houston’s wind patterns for their effectiveness (“Air Pollution Control Technology Fact Sheet,” n.d.). However, there are setbacks to these methods that make them less convenient to implement, such as the fact that both combustion unit types are noisy, produce large amounts of heat and have little aesthetic value (The Clean Air Technology Center, 2003). Additionally, they require high implementation and maintenance costs in order to achieve high efficiencies, as mentioned in the previous paragraph. It is also important to note that their requirement for an auxiliary fuel creates additional costs and decreases their effectiveness in preventing pollution.

**Alternative Pollution Cleaning Methods: Bio-Filters**

Bio-filters are systems that utilize microbes to break down air pollutants through metabolic reactions, and convert them into carbon dioxide, water vapor and organic biomass (Devinny et al., 1999). In a bio-filtration system, microorganisms such as bacteria, protozoa and algae, grow in the surface of a
porous medium, usually composed of peat, compost, coarse soil and other materials, which ensure that the organisms have a stable nutrient supply (Devinny et al., 1999). As polluted air passes through the porous bed media, the particles are absorbed by moisture and exposed to microorganisms, which reduce the concentration of pollutants through metabolic enzymes (The Clean Air Technology Center, 2003). Figure 4.2 shows a basic bio-filtration system, where the contaminated air of a building or process is collected through an air fan and transported into a plenum (a *plenum* refers to a pressurized chamber used to contain gases). The plenum is perforated with holes so that the polluted air can pass into the bed media, and any excess bed moisture is allowed to exit into a drain or wastewater treatment. Once the polluted air passes through the medium, the microorganisms then break down the pollution particles and release CO$_2$ into the air. Figure 4.3 displays a variation of the basic bio-filter model, where a portion of the released byproduct runs through the bio-filter multiple times by adding a cover and vent to redirect the exhaust flow (The Clean Air Technology Center, 2003). This process maximizes the contact time with microbes to enhance the air quality of the exhaust before its release.

![Figure 4.2. Basic Bio-Filtration Process Diagram and Image. Sources: The Clean Air Technology Center, 2003; Geoplast, n.d.](image-url)
Bio-filter advantages as compared to other methods of air pollution is that they are highly effective in degrading VOC’s without requiring new technologies. Table 4.2. displays the efficiency of bio-filters in degrading several pollutants, many of which are present in the Houston Ship Channel (this point will be discussed in further detail in chapter five). Additionally, installation costs for these systems are very low, as the necessary construction materials are available locally (lumber, fiberglass, plastic pipes, etc.) and the structures can be built with local labor such as carpenters, plumbers and earthmovers (The Clean Air Technology Center, 2003). However, a setback of the traditional design is its large area requirements due to its horizontal bed layout. Typical areas will range from 100 to 22,000 square feet, depending on the type of pollutants and their volumes (Leson and Winer, 2012). The determination of an area is extremely site specific, and there is a high variability of areas within known implementation projects. Therefore, the area requirements for a horizontal bio-filter would play a pivotal role on the feasibility of its implementation, and need to be determined based on the specific needs of a site prior to the design process. A typical design modification to avoid such area requirements is to stack individual beds on top of each other, as shown in Figures 4.4 and 4.5. Vertical stacks, such as the one in the A diagrams, minimize the required space and can lower the costs of a project depending on the types of
pollutants being filtered (Leson and Winer, 2012). A final advantage of bio-filters is that, due to the
natural processes they implement to degrade pollutants, plants can be integrated into the bio-filtration
process to enhance their aesthetic value. The following two subsections address modern implementations
of bio-filters in design, which explore the possibilities of enhancing public spaces visually through the use
of bio-filters.

Figure 4.4. Diagram Comparison of a Stacked (A) versus a Horizontal (B) Layout in a Bio-filtration System.

Figure 4.5. Images of a stacked (A) Bio-filter versus a horizontal (B) Bio-filter. Sources: AP Business Technology
Consultancy, n.d.; Iowa State University, n.d.
### Effectiveness of Bio-filters in Degrading Different Compounds

<table>
<thead>
<tr>
<th>Aliphatic hydrocarbons</th>
<th>Oxygenated carbon compounds</th>
<th>Nitrogen-containing carbon compounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>Alcohol</td>
<td>Amines</td>
</tr>
<tr>
<td>Propane</td>
<td>Methanol</td>
<td>Aniline</td>
</tr>
<tr>
<td>Butane</td>
<td>Ethanol</td>
<td>Nitriles</td>
</tr>
<tr>
<td>Pentane</td>
<td>Butanol</td>
<td>Acrylonitrile</td>
</tr>
<tr>
<td>Isopentane</td>
<td>2- Butanol</td>
<td>Pyridine</td>
</tr>
<tr>
<td><strong>Hexane</strong></td>
<td>1- Propanol</td>
<td><strong>Sulfur-containing carbon compounds</strong></td>
</tr>
<tr>
<td>Cyclohexane</td>
<td>2- Propanol</td>
<td>Carbon disulfide</td>
</tr>
<tr>
<td>Acetylene</td>
<td>Aldehydes</td>
<td>Dimethyl sulfide</td>
</tr>
<tr>
<td>Aromatic hydrocarbons</td>
<td>Formaldehyde</td>
<td>Dimethyl disulfide</td>
</tr>
<tr>
<td>Benzene</td>
<td>Acetaldehyde</td>
<td>Methyl mercaptan</td>
</tr>
<tr>
<td>Phenol</td>
<td>Carbonic Acids</td>
<td>Thiocyanates</td>
</tr>
<tr>
<td><strong>Toluene</strong></td>
<td>Butyric acid</td>
<td><strong>Inorganic compounds</strong></td>
</tr>
<tr>
<td><strong>Xylene</strong></td>
<td>Vinyl acetate</td>
<td>Ammonia</td>
</tr>
<tr>
<td>Styrene</td>
<td>Ethyl acetate</td>
<td>Hydrogen sulfide</td>
</tr>
<tr>
<td>Ethylbenzene</td>
<td>Butyl acetate</td>
<td><strong>Nitrogen Oxide</strong></td>
</tr>
<tr>
<td>Chlorinated hydrocarbons</td>
<td>Ethers</td>
<td></td>
</tr>
<tr>
<td>Carbon tetrachloride</td>
<td>Diethyl ether</td>
<td></td>
</tr>
<tr>
<td>Chloroform</td>
<td>Dioxane</td>
<td></td>
</tr>
<tr>
<td>Dichloromethane</td>
<td>Methyl tert-butyl ether</td>
<td></td>
</tr>
<tr>
<td>Bromodichloromethane</td>
<td>T tetrahydrofuran</td>
<td></td>
</tr>
<tr>
<td>Tetrachloroethene</td>
<td>Ketones</td>
<td></td>
</tr>
<tr>
<td>Trichloroethene</td>
<td>Acetone</td>
<td></td>
</tr>
<tr>
<td>Vinyl chloride</td>
<td>Methyl ethyl ketone</td>
<td></td>
</tr>
<tr>
<td>1,2- Dichlorobenzene</td>
<td>Methyl isobutyl ketone</td>
<td></td>
</tr>
<tr>
<td>Chlorotoluene</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Legend:**

1. Some Biodegradability
2. Moderate Biodegradability
3. Good Biodegradability
4. Unknown

- Compound found in air releases of examined industries

Table 4.2. Effectiveness of Bio-filters in Degrading Different Compounds. Data Source: Devinny et al., 1999.
Figure 4.6. Green Wall Biofilter, five stories high, installed in Drexel University. Source: Diamond Schmitt Architects, n.d.

Bio-filters Applied in Design: Living Wall Biofilters

Designed by: Diamond Schmitt Architects

Status: Constructed

The concept of bio-filtration has been applied in landscape design through the incorporation of green infrastructure in indoor ventilation systems, mostly used to clean indoor air pollutants in large building complexes such as the one displayed in Figure 4.6. Bio-filter green walls are a modification of a method often used in wastewater treatment, called a trickling filter. This technology consists of a vertical tank containing a packed bed of aggregate, ceramic or plastics and a vertical pipe through the center, with rotating water sprays at the top that distribute the water evenly over the upper surface of the tank. The water trickles through the packed bed, where the microbes decompose pollutants on the wastewater. The remaining water is then recirculated through the system by using a pump to transport the water up to the rotating sprays. This entire process is shown in Figure 4.7. In the case of bio-trickling filters, such as the living wall shown above, the pollutants are first absorbed from the air phase into the liquid phase by microbes (The Clean Air Technology Center 2003). Living walls apply the bio-trickling system and
incorporate it into a building’s ventilation system, where contaminated air inside a building is exposed to microbes in the plant roots through holes in a vertical plenum. Once the filtered sludge reaches the bottom of the planting bed, it is recirculated upwards through a pump, where it can be taken through the filtering process once more or released back into the space. A basic detail of how a bio-trickling filter is modified to fit a living wall setting is shown in Figure 4.8.

![Figure 4.7. Traditional Trickling bio-filter. Source: Clean Air Technology Center, 2003.](image)

The process of breaking down pollution particles is carried out by plants and the microorganisms inhabiting their rhizosphere. Some microorganisms that perform these tasks are also known to enhance the growth of their host plants, such as \textit{Azotobacter}, \textit{Alcaligenes}, \textit{Arthrobacter}, \textit{Bacillus}, \textit{Serratia}, and \textit{Rhizobium} (Soreanu et al., 2013). It is also interesting to note that this implementation type of a bio-filter has the opportunity to clean up its own production of carbon dioxide through the photosynthetic processes occurring in plant leaves, simultaneously to the particle degradation process in the roots (Soreanu et al., 2013). According to a literature review realized to compare performance levels of green wall bio-filters versus regular trickling filters, the green wall method was more effective in keeping microorganism population and diversity, due to the generation of exudates on the plant roots (\textit{Exudates} are substances
that ooze out of plant tissue pores and often include nutrients that are beneficial for bacteria and fungi (Walker et al., 2003)). These fluids secreted by roots are an important source of sugars and amino acids for rhizosphere microorganisms (Soreanu et al., 2013). Meanwhile, traditional filters are limited by the substrate availability in the beds of the system.

In terms of design, living bio-filters are aesthetically compelling and can become focal points in the design of a building. They are visually pleasing, and can be easily installed in many types of architectural structures. However, it is important to note that creating a stable environment for the plants plays a key component in ensuring the success of the bio-filter as a whole. One potential option for implementing this strategy in an outdoor setting could be to refer back to the design alternative shown in Figure 4.3, which utilizes a cover to regulate temperature and prevent the release of gases. Moreover, in order to adapt this method into an outdoor setting, it would be beneficial to incorporate a fan system into the building structure in order to attract pollution particles to the wall. One possible example of this system is shown in the following sub-section.
Bio-filters Applied in Design: The City Tree Bench

Figure 4.9. City Tree bench, by Green City Solutions. Source: GreenCity Solutions, n.d.

Designed by: Green City Solutions

Status: Constructed

The Moss Bench by Green City Solutions (shown in Figure 4.9) is a bio-filter that utilizes a select variety of moss species, which absorb harmful toxins such as particulate matter and nitrogen oxides, and simultaneously produce oxygen (GreenCity Solutions, n.d.). The project is a combination of nature and technology, implementing mosses to absorb air particulates, while using a system of sensors built into the bench structure to monitor the microclimate of the mosses and ensure their survival in urban settings. In the design shown in Figure 4.9, the sensors send information via wireless signals to a corporate cloud, in order to evaluate the performance of each bench and maintain the habitat standards of the moss species (GreenCity Solutions, n.d.).
If needed, the energy required by the bench structure to maintain the microclimate of the moss is provided by solar panels or by a grid connection in the system (GreenCity Solutions, n.d.). Water provision for the moss is also either connected to the city grid or independent, although the company does not specify how the independent irrigation system operates.

![Monitoring system to track performance rates and microclimate stability. Source: Green City Solutions, n.d.](image)

According to the partners and creators of the Moss Bench, the average observed PM efficiencies of a single structure are of approximately 19%, 15%, and 11% for PM10, PM2.5 and PM1, respectively (GreenCity Solutions, n.d.). The bench performance rates are enhanced through an integrated ventilation system in the wall structure that absorbs air, making the structure independent from natural wind patterns and increasing the flexibility of where it can be placed (GreenCity Solutions, n.d.). The company also performed a variety of tests with bio-filter corporations to determine the appropriate types of mosses for the bench, but the information on which moss species they used was undisclosed.

In terms of design, the strength of the Moss Bench lies in its flexibility. The structure of the design not only ensures the survival of the mosses, but also serves as a seating feature that can be placed in a variety of settings, as shown in Figure 4.11. Because of its efficient size, the
structure can also be transported to different locations according to air quality levels at any given date. Another strength of the design was its use of an active ventilation system, in order to maximize the performance of the bench and minimize its dependence on local wind patterns. Because of these qualities, the bench can be placed in any location and become an aesthetic, visually engaging object that is educational, environmentally beneficial, and useful as seating.

Since the creation of the bench in 2014, it has since been applied in ten different countries. (GreenCity Solutions, n.d.). However, it is important to note that all of the countries in which the benches were implement are located in Europe, usually in cities that have high levels of ozone and particulate matter, but not of certain types of VOCs that are present in the Houston context (GreenCity Solutions, n.d.). Moreover, while the cost of implementation for a single bench is not disclosed, it is likely that the wireless sensor system is expensive to implement for communities that have a limited budget, such as the communities of East Houston.

![Figure 4.11. Renderings of bench implemented in commercial and corporate settings. Source: GreenCity Solutions, n.d.](image)

**Modern Pollution Cleaning Methods: Photocatalysis of Air Pollutants through Titanium**

Modern methods of absorbing air pollution have experimented with other natural processes involving chemical reactions. Photocatalytic reactions are a process commonly used on indoor air purification. The
process, shown in Figure 4.12, consists of exposing a semiconductor like a metal oxide or sulfide to ultraviolet light radiation in order to release electron particles that interact with water particles found in the air (Kaneko and Okura, 2003). This interaction forms hydroxyl radicals, uncharged particles that are highly reactive, that break down the chemical bonds of carbon based compounds, like VOC’s (Kaneko and Okura, 2003). Commonly known semiconductors include titanium, zinc, tungsten trioxide, tin, zirconium, iron oxide, vanadium oxide, and ilmenite (Zaleska et al., 2010). From this list, titanium (TiO₂) is the most researched and implemented for air purification, as it is non-toxic, durable and highly active during photo-catalysis, which indicates that it can completely degrade a wide range of pollutants (Zaleska et al., 2010). Most importantly, titanium photo-catalysis has a high efficiency for removing the target VOCs found in the Houston Ship Channel, as shown in Table 4.3. However, there is not much research available in its efficiency for degrading particulate matter.

Figure 4.12. Photocatalytic Air Purification Process Diagram. Source: Arizona State University Zentox Corporation, n.d.
Table 4.3. Removal Efficiency of Titanium Photocatalysis for certain VOCs. Source: Huang et al., 2016.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Removal (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetone, toluene p-xylene</td>
<td>77–62</td>
</tr>
<tr>
<td>Acetaldehyde</td>
<td>99+</td>
</tr>
<tr>
<td>Toluene</td>
<td>99+</td>
</tr>
<tr>
<td>Benzene</td>
<td>100</td>
</tr>
<tr>
<td>m-Xylene</td>
<td>99+</td>
</tr>
</tbody>
</table>

Photo-catalysis has been introduced into architecture in order to combat outdoor air pollution, by coating materials with titanium dioxide that reacts with natural sunlight. Figure 4.13 displays a building façade that uses such technology at the Manuel Gea Gonzales hospital in Mexico City, created by Elegant Embellishments. The façade has been installed in many locations around the world, including Australia, United Arab Emirates, and Mexico (Elegant Embellishments, n.d.). This is due to the modular structure of the wall, shown in Figure 4.14, which consist of easily assembled and transportable parts.

Figure 4.13. Prosolve370e by Elegant Embellishments, Mexico City. Source: Elegant Embellishments, n.d.
Designed by: Elegant Embellishments

Status: Constructed

As a design project, the strength of the Prosolve370e façade is its form. The designers of Elegant Embellishments were inspired by the forms of coral reefs and their growth (Elegant Embellishments, n.d.). This form works in favor of the design because it is fractal, so it maximizes the surface area of the façade while keeping a stable volume. Consequently, more area of the wall is exposed to air and sunlight, which maximizes the decomposition of pollution particles. As a design element, the form allows for visibility within the building, and creates an interesting and engaging shape. However, it is important to note that the façade depends on local wind patterns in order to attract pollution particles to its surface. Another possible challenge in the implementation of such technology is that it is relatively new, expensive, and still being tested. For example, one study found the generation of 11 gaseous byproducts in the removal of benzene through titanium photo-catalysis (Han et al., 2007). These byproducts included 2-methylpropene, acetaldehyde, acetone, pentane, methylcyclobutane, methylcyclopentane, cyclohexane, 2,3-dimethylbutane, 2-methylpentane, 3-methylpentane, and hexane (Han et al., 2007). Although none of them are as toxic as benzene, some of them are still included on the list of targeted pollutants in the
channel. The study attributed the generation of these gases to lower levels of humidity within the system, which suggests that the process of photo-catalysis should be closely monitored in order to prevent these unwanted byproducts (Han et al., 2007).

From the different methods analyzed in this chapter, bio-filters and photo-catalysis have great potential to work in the Houston context, as they are highly efficient at VOC removal without the requirements of outside fuel sources. However, both of these methods need constant monitoring in order to ensure their correct operation. Thermal and catalytic control units can also achieve high removal efficiencies, but only though the use of an outside fuel to increase the temperature of the units. In terms of implementations and monitoring costs, photo-catalysis is potentially the most expensive to implement, as it is the newest type of technology. Bio-filters can also potentially require higher implementation costs if they have specialized modifications (such as with the city-tree bench), but are the cheapest option on their basic horizontal form. Moreover, bio-filters do not depend upon wind-patterns in order to function, as they are connected through piping to the VOC source. Figure 4.15 provides a matrix over the advantages of each removal method.

Besides the criteria evaluated on the matrix, there are many components to consider when applying any of these methods to the Houston context. The petrochemical corridor requires a solution that treats pollutants on site, as the ship channel area is largely dense and there is not much space available to implement off-site options. Preferably, this on-site solution should absorb and eliminate pollutants without releasing them into the atmosphere, as this reduces the risk of contact between polluted air particles and people living adjacent to industries. Moreover, treating the pollutants before they are released into the atmosphere would avoid the challenge of depending on wind-patterns for the applied solution to work effectively, and eliminate the cost of air fans that attract pollution particles into the system. Finally, the solution should have high removal efficiencies of the types of VOC’s found in the channel, and should be a cost effective option in order for the design’s implementation to be feasible. The
following chapter will discuss how bio-filters are an effective method to fulfill all of these requirements, while providing opportunities for education and recreation in the channel.

Figure 4.15. Comparison Matrix of different pollution removal methods.
Chapter 5
The Community of Manchester and Valero Oil Refinery

From the information discussed in the previous chapter, bio-filters emerge as an efficient and cost-effective choice to reduce emissions from point sources in the Houston Ship Channel. Bio-filtration has the potential to eliminate emissions for specific industries, while generating opportunities to create public spaces and engage people in the design solutions. However, due to the limited available space in the Houston ship channel and the varying levels of bio-filter efficiency for different VOC’s, it is necessary that the solution implements a combination of different types of bio-filters in order to tackle pollution most effectively. This chapter discusses the reasons why bio-filters would be an effective choice for specific sites within the Houston Ship Channel, and introduces the design concept for the project. Additionally, the chapter presents an overview of how the concept can be applied in fence-line community conditions, using as an example the site of Valero Refining Systems Inc. and the fence-line community of Manchester.

Bio-filters as a Possible Solution for Houston’s Air Pollution

Bio-filters have the potential to be successful in cleaning pollutants from specific point sources within the Houston Ship Channel because they are effective in breaking down many of the VOC’s observed on the site. This is illustrated in Table 4.2, which identified the effectiveness of bio-filters in breaking down various types of air particulates in the previous chapter. When compared to Tables 5.1, 5.2 and 5.3, which display the air pollutant emissions of three different industries located along the channel, the contents of Table 4.2 make it clear that bio-filters have a moderate to high potential to break down most of the substances being produced in these industries. It is also important to note that the pollutants listed on Table 5.1 as only having moderate removal efficiency still get mostly decomposed by bio-filters, which greatly reduces their impact on the environment. For example, in a study conducted to test the
effectiveness of bio-filters in degrading n-hexane, a pollutant emitted in all three of the discussed industries with a moderate bio-filtration success rate, the experiment found that bio-filters still had a 76% removal efficiency when n-hexane was released into the bio-filter without the presence of other gases (Amin et al., 2017).

The industry presented in Table 5.1, the Valero Refinery, offers a unique opportunity for implementing bio-filters in order to reduce its air pollutant emissions. As seen in Figure 5.1, all three industries have communities located close to their perimeters. However, the community of Manchester near the Valero Refinery is a fence-line community, meaning that it is located adjacent to the refinery border. This community is composed of a largely Hispanic, low-income population and has a history of high pollution levels. The community was established in the 1860s, as a switch between the Texas and New Orleans railroad (Kleiner, 2010). However, the Manchester Terminal Corporation built a ship terminal in the area during the 1920’s to handle cotton exports (Kleiner, 2010). By the 1970s, the area had become largely industrial, and had already acquired a predominantly Hispanic population (Kleiner, 2010). At the beginning of the 2000’s, the area was defined as a toxic spot due to heavy industrial activity, as air monitoring stations often detected high levels of butadiene (Kleiner, 2010).

### Valero Houston Refinery

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Total Released</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen Cyanide</td>
<td>1,260,408 pounds</td>
<td>52.5%</td>
</tr>
<tr>
<td>Ammonia</td>
<td>322,866 pounds</td>
<td>13.37%</td>
</tr>
<tr>
<td>Ozone</td>
<td>268,066 pounds</td>
<td>11.10%</td>
</tr>
<tr>
<td>Toluene</td>
<td>117,288 pounds</td>
<td>4.86%</td>
</tr>
<tr>
<td>Xylene</td>
<td>89,654 pounds</td>
<td>3.71%</td>
</tr>
<tr>
<td>Benzene</td>
<td>53,029 pounds</td>
<td>2.20%</td>
</tr>
<tr>
<td>N- Hexane</td>
<td>50,643 pounds</td>
<td>2.10%</td>
</tr>
<tr>
<td>Others</td>
<td>252,430.88 pounds</td>
<td>10.46%</td>
</tr>
</tbody>
</table>

### Pasadena Refining Systems Inc.

Total chemical air releases in the past decade: 3,389,349.65 pounds

<table>
<thead>
<tr>
<th>Substance</th>
<th>Percentage</th>
<th>Pounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulfuric Acid</td>
<td>25.2%</td>
<td>854,516.80</td>
</tr>
<tr>
<td>Propylene</td>
<td>21.25%</td>
<td>720,163.62</td>
</tr>
<tr>
<td>N-Hexane</td>
<td>19.54%</td>
<td>662,404.20</td>
</tr>
<tr>
<td>Xylene</td>
<td>9.75%</td>
<td>330,512.78</td>
</tr>
<tr>
<td>Ethylene</td>
<td>5.18%</td>
<td>175,561.74</td>
</tr>
<tr>
<td>Hydrogen Cyanide</td>
<td>4.48%</td>
<td>151,882.33</td>
</tr>
<tr>
<td>Toluene</td>
<td>4.16%</td>
<td>140,962.85</td>
</tr>
<tr>
<td>Benzene</td>
<td>3.04%</td>
<td>102,895.38</td>
</tr>
<tr>
<td>Others</td>
<td>11.55%</td>
<td>391,412.80</td>
</tr>
</tbody>
</table>


### Foster Products Corp.

Total chemical air releases in the past decade: 73,830.06 pounds

<table>
<thead>
<tr>
<th>Substance</th>
<th>Percentage</th>
<th>Pounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>N-Hexane</td>
<td>95.35%</td>
<td>70,394.80</td>
</tr>
<tr>
<td>Toluene</td>
<td>2.66%</td>
<td>1,964 pounds</td>
</tr>
<tr>
<td>1,2-4 Trimethylbenzene</td>
<td>1.82%</td>
<td>1341.51 pounds</td>
</tr>
<tr>
<td>Cyclohexane</td>
<td>0.17%</td>
<td>128.95 pounds</td>
</tr>
<tr>
<td>1,3-Butadiene</td>
<td>0.005%</td>
<td>0.40 pounds</td>
</tr>
<tr>
<td>Styrene</td>
<td>0.005%</td>
<td>0.40 pounds</td>
</tr>
</tbody>
</table>

Table 5.3. Foster Products Corp. Air Pollution Emissions. Source: EPA TRI Facility Report, n.d.
Figure 5.1. Location of the Industries of Valero Refining Systems Inc., Pasadena Refining Systems Inc., and Foster Products Corp., as compared to the location of low-income communities such as Manchester, Magnolia Park and Pasadena Place.

Currently, the area is still comprised of a majority Hispanic population, with close to a third of its residents earning a lower income than that of the poverty level, as shown in Table 5.4. The average income in the area is of approximately $37,513 a year ("Harrisburg - Manchester Demographics," n.d.). It is also important to note that over one third of the population is under the age of 20 years (Community Health Profiles, n.d.). This is because air pollution exposure can be particularly harmful during the physiological development stages, and can lead to a variety of chronic diseases and a shortened life expectancy (World Health Organization, n.d.). The two leading causes of death within the community of Manchester are
Heart Disease and Cancer; both occur at higher rates in this community than in Houston as a whole. Heart disease mortality rate in Manchester is of 336.8 per 10,000 deaths as compared to 262.0 in Houston, and the cancer mortality rate is 248.4 per 10,000 deaths in Manchester as compared to 197.6 in Houston (Community Health Profiles, n.d.). Additionally, the death rate for chronic diseases as a whole is also higher in Manchester than Houston, with a rate of 1192.8 per 10,000 deaths in Manchester compared to a rate of 898.2 in Houston (Community Health Profiles, n.d.).

Demographics of the Manchester Community

Due to the conditions of the Manchester community, the Valero refinery is a good site for mitigation due to its large amount of emissions and the comparable incidence of disease in this fence-line community. The Valero facility has the third largest amount of on-site releases in the entire city of Houston, with 578,703 pounds of total contaminant releases in 2016, 58% of which were air releases (338,604 pounds; EPA TRI Facility Report, n.d.). The community of Manchester is directly adjacent to this site, as shown in images such as Figure 5.2. The close proximity of Manchester’s residents to the refinery could be a possible cause of the higher death rates due to chronic diseases, making this area a priority for improvements. Additionally, the close proximity increases the tension between the refinery...
and community residents who believe their health is being put at risk. During the research for this thesis in June of 2018, for example, the Valero Refinery requested a permit amendment to the Texas Commission on Environmental Quality (TCEQ), which would allow the refinery to release hydrogen cyanide into the atmosphere (Trovall, 2018). The refinery claims that the released cyanide concentrations are low enough that they will not put residents at risk. However, as previously shown in Table 4.2., hydrogen cyanide is already released yearly by the refinery in high quantities, more than any other pollutant it releases. Manchester’s inhabitants are also skeptical about the health-risks that this specific pollutant poses, as they expressed during a public meeting between TCEQ, Valero, and the community. Residents reported health-related issues, such as constant nosebleeds, asthma and headaches (Coates, 2018). These could potentially be caused by hydrogen cyanide, as this chemical is a neurotoxin known to cause headaches, weakness, nausea and enlarged thyroid (Coates, 2018). However, the executive director of TCEQ has already granted Valero preliminary approval for the permit, which has increased tensions between the industry and the residents, as they feel their health is not being taken into account (Coates, 2018).

Figure 5.2. House in Manchester next to the Valero Gas Tanks. Source: Trovall, 2018.
To prevent these sorts of issues, it is imperative that Valero finds a solution to decrease their pollution emissions, preferably without releasing them into the atmosphere. In this sense, bio-filters could be a possible way for the Valero Oil Refinery to improve its relation with its surrounding communities, which would be beneficial for them, as many of Manchester’s residents are also employees in this establishment (Coates, 2018). Bio-filter implementation would also improve the living conditions of the Manchester community, and create the opportunity to offer them a public space through an ‘industry buffer’ strategy. This strategy will be presented in the following subsection.

**Design Concept: Softening the Edge**

There are three main goals that the introduction of bio-filters into the Manchester and Valero site should accomplish: firstly, to decrease air pollution emissions of the refinery through the absorption and degradation of pollutants, without releasing them into the atmosphere; secondly, to improve relations between the refinery and the community, by educating residents about the benefits of bio-filters as a design improvement that is beneficial for their health; and finally, to create recreational opportunities that engage people with these design improvements and raise their quality of life. These goals could be accomplished through the creation of a public space, which breaks the hard, fence-line ‘edge’ between the industry and the community, and instead transforms it into a transitional buffer zone. This public space could implement a variety of bio-filters to mitigate air pollution from the refinery, and simultaneously serve as a place where bio-filters and the community residents can co-exist. One possible location for such space could be the empty parking lots and abandoned lots in the refinery’s edge, shown below in Figure 5.3.
The three spaces shown above have potential for recreational uses. Blocks 1 and 2 are currently being used as a parking and storage space for the Valero refinery. Meanwhile, Block 3 is currently a park and recreational center, which could be incorporated into a possible design. The division of the blocks could also be used to delineate the division of the different bio-filters that are integrated into the space. Figure 5.4 illustrates a possible division of three different types of bio-filter strategies. These strategies include a vertical bio-filter on the edge of the refinery, a series of medium-sized trickling bio-filters in the first block, which incorporate vertical planting on their surface to add aesthetic appeal to the space, and a large horizontal bio-filter in the second block, which is underground, but allows residents to look inside through a glass cover.
One possible challenge in implementing this strategy is that the idea of encouraging people to inhabit spaces near active industrial sites is generally unheard of. However, there are several existing precedents that prove this type of public spaces exist and can be implemented successfully. One such example is the Metabolon Park in the Leppe Waste Disposal site, Lindlar, Germany. This park, designed by the firm FSW Landscape Architects, is located within the boundaries of an active landfill and recycling center, but has a space reserved for educational and recreational use (“Metabolon,” n.d.). The main feature of the park consists of a mountain made from the ashes of burned waste, which was then accumulated and covered with a special filter fabric, to allow humans to walk over the pile (shown in image A of Figure 5.5) (“Metabolon,” n.d.). Figure 5.5 illustrates some of the ways in which the park offers recreational and educational uses, such as the outside classroom/playroom at the top of the mountain (B), and rooms created out of waste, which are also used as classrooms for children (C).
The use of this park as a precedent is helpful for this project in two ways: Firstly, it is an example of how public spaces near active industrial sites can be implemented safely and successfully. Secondly, the phasing plan of the Metabolon considers the future of the space after closure of the landfill, and foresees the gradual expansion of the park as the landfill reaches its maximum capacity. These two factors offer a few things to consider when designing a similar type of public space in the Houston context. One of them is that understanding the processes and reactions taking place in each individual industry is imperative in ensuring the safety of visitors. The design should maintain areas that are designated towards public use, and areas that are strictly reserved for industrial use only and do not allow public access. However, the Metabolon design uses a variety of methods that allow visitors to witness the activities that happen in these areas without entering, such as high mounds and elevated walkways. This could be especially helpful in the design for a public space near Valero, as the area is relatively flat and does not provide any natural opportunities to look at the industrial processes happening within the refinery. Another important takeaway is the importance of creating experiences within the public space that engage people with educational elements, so they can further appreciate the significance of the processes they witness. In the Metabolon case, this point is achieved through the “waste mountain” and the outside classroom within the top (shown in Figure 5.5.), as well as the variety of exhibition spaces and playgrounds scattered throughout the park (some of these spaces are shown in Figure 5.6.).
Another aspect which is helpful to analyze in the Metabolon design is the consideration of park expansions as the landfill reaches its maximum capacity. Currently, the landfill operates by stacking new piles of ash waste on different zones around the “waste mountain,” which will all be covered in the future with the same protective textile as the main mountain to allow human access. The landfill is projected to close during 2020-2021, so the designers of the metabolon have already prepared a plan of possible program uses for these smaller mounds as the park begins to close. Although the Valero Refinery is not predicted to close any time in the near future, considering a phasing plan for the park could be beneficial to the design process of the three available blocks. The design of the blocks should consider how the bio-filter infrastructure could be used in ways that are still engaging if their original usage becomes obsolete. Additionally, the blocks should consider possible connections to the channel in case of Valero’s closure, as this would greatly enhance the quality of the space.

From the analysis of Metabolon Park, it can be concluded that creating a public space that allows positive interactions between community residents and industrial processes to happen has the potential to improve relations between Manchester and Valero. Additionally, celebrating these processes through public engagement can generate a sense of pride and identity within the community. All of these aspects could be beneficial in the Valero and Manchester context, as they would turn an object that is constantly seen as hazardous and unappealing (the refinery), into an integral part of the community’s identity, which