REMEDIATING MODULES: PREFABRICATED COMPONENTS FOR IMPROVING INDOOR AIR QUALITY

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HEALTH AS A DESIGN DRIVER

The United States Environmental Protection Agency (EPA) designates indoor pollution as one of the top five largest environmental threats to human health in their Report to Congress on Indoor Air Quality (IAQ). In the same report the EPA noted, "Indoor air quality problems caused at least in part by the way in which buildings are designed and operated pose far more significant problems than had been previously recognized by various levels of government" (U.S. Environmental Protection Agency (EPA), 1989, p. 4). Over 20 years have passed since the EPA made these comments, and architects still pay relatively little attention to designing for indoor air quality. In general, the issue is addressed by providing ventilation of indoor spaces with outdoor air. Therefore, design for indoor environmental quality falls largely within the purview of the engineer who designs mechanical systems to regulate temperature, humidity, and ventilation rates.

The sources of interior pollutants are varied and extensive. Volatile organic compounds (VOCs) are released by paints, adhesives, caulking, ceiling tiles, cleaning products, fabrics, plastic grocery bags, beauty products, air fresheners, plywood, particleboard, and equipment including computers, televisions, and photocopiers (Wolverton & Kozaburo, Plants: Why You Can't Live Without Them, 2010, pp. 14-20). Biological contaminants, including mold and fungus, may grow indoors usually as the result of excess moisture. Indoors, particulates are generated by abraded surfaces such as upholstery, carpet, flooring materials, and our clothing (McDonough & Braungart, 2001, pp. 3-4).

Outdoors, particulates may be produced as the result of combustion from automobiles, manufacturing, and power plants. Particulates are also generated when gasses combine, or by natural sources such as plants and dust storms (ASHRAE Special Project 200, 2009, p. 54). Many toxins are brought to the interior from the exteriors. One example is ozone, which is produced when VOCs and Nitrogen oxides (often from cars) react in the presence of sunlight. Ozone may have indoor concentrations that are higher than outdoors, yet ozone is not a pollutant derived from indoor sources (ASHRAE Special Project 200, 2009, p. 54). Together VOCs, gasses, biological contaminants, and particulates form a potentially toxic soup with unknown and unpredictable chemical behavior, and therefore unpredictable effects on building inhabitants.

There are two branches that combined constitute the complete *indoor environmental quality* of a space. The branch that addresses human thermal comfort parameters such as air temperature, relative humidity and air velocity, is referred to as the *condition* of indoor air. The branch that addresses gasses and aerosols, whether harmful or not, is referred to as the *quality* of indoor air. Ailments caused by extreme temperatures can be serious and can have permanent bodily effects. Within the normal indoor temperature ranges, common health complaints would include dry mouth, nose, and eyes, with cold hands and feet at one end of the spectrum and excessive sweating, stress, and danger of heat stroke at the other extreme.

Human beings have created structures for thousands of years specifically to control the *condition* of the indoor environment so that we may be relatively comfortable. The pursuit of thermal comfort is fundamental to why we build at all. Because of this, there have been vast amounts of human energy invested in methods of both passively and actively controlling the condition of indoor air. Today, our confidence in the efficacy of our mechanical heating and cooling systems is materially indexed by the appearance of predominantly glass buildings around the world, whether in the tropics, the arid desert, the temperate zones, or the cold northern and southern latitudes. These structures have started to replace vernacular materials, forms, and space distributions that were derived in order to maintain locally specific environmental comfort. Thermal comfort control is an ancient science with a range of tested possible approaches. Whether these approaches rely on natural bioclimatic energy flows or fossil fuel powered equipment is a conversation beyond the scope of this paper. What is important though, is that this branch of environmental control has had a long period of incubation.

The branch of environmental quality that is younger and less mature is that of air quality. Many of the decisions that humans have made in pursuit of thermal comfort, may have simultaneously created toxic air content that is a slow silent poison. The topic of air quality has been around for hundreds of years, but it's only been since the identification of two diseases linked with exposure to indoor air in the last 40 years that the topic has gained significance and merit. Sick building syndrome (SBS) is often defined as eye, nose, throat irritation, sore throat, headache, fatigue, skin irritation, mild neurotoxic symptoms, nausea, and irritation with building odors persisting for more than two weeks affecting at least 20 percent

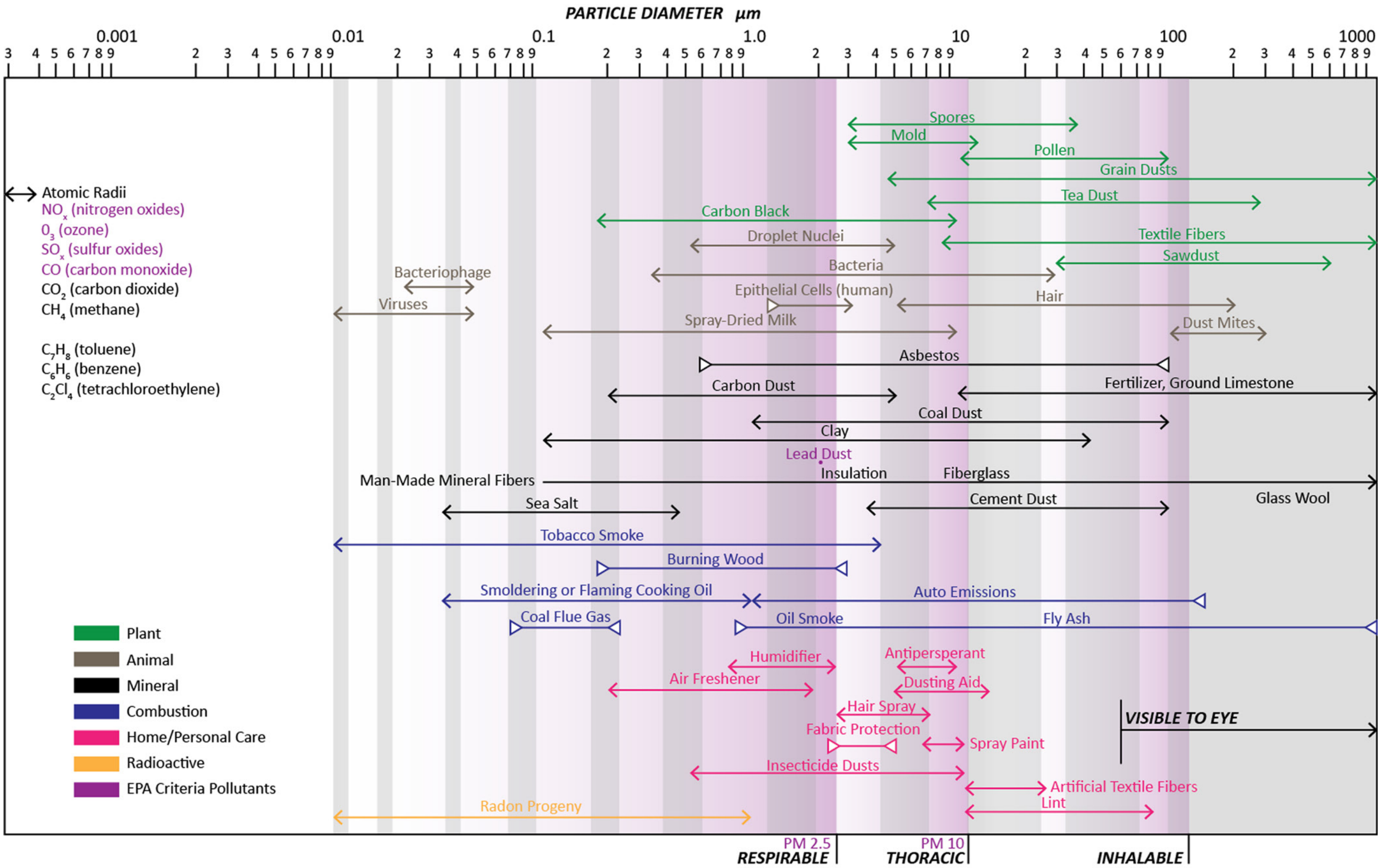

Figure 1. Particle sizes shown with human respiratory limit

of the buildings' occupants and who report relief upon exiting the building (ASHRAE, 2009, p. 10.1). Because the symptoms of SBS are wide-ranging and non-specific, a universally agreed upon definition is lacking.

Building-related illnesses (BRI) differ from SBS in that an origin can be identified. Physical signs of abnormalities that can be clinically identified often accompany building-related illnesses. For example, hypersensitivity illnesses including pneumonitis, humidifier fever, asthma, and allergic rhinitis, are all caused by individual sensitization to bioaerosols (ASHRAE, 2009).

The health risk potential of any aerosol is dependent on several factors: the dimension and durability of the toxin, the potency of the toxin, the susceptibility of the person exposed, the concentration of the toxin, and the duration of exposure (ASHRAE, 2009, p. 10.3). The dimensions of common indoor aerosols are graphically represented in Figure 1 along side notation for limits of human respirability. Respirable particles vary in size from <1 to 10 µm (micrometers or microns). Particles larger than 8 to 10 µm are primarily separated and retained by the upper respiratory tract. Intermediate sizes are deposited mainly in the conducting airways of the lungs, from which they are swallowed or coughed out. Fifty percent or less of the particles inhaled settle in the respiratory tract. Submicron particles penetrate deeper into the lungs, but many do not deposit and are exhaled (ASHRAE, 2009, p. 10.4).

Each of the hundreds of VOCs has its' own effect on health. Formaldehyde is a Group B1 carcinogen with a high probability of contributing to lung and nasopharyngeal cancer. Benzene inhalation may cause drowsiness, headache, and eye, skin, and respiratory tract irritation. Benzene also has negative reproductive effects, and has factually been linked to leukemia, making it a Group A carcinogen (EPA (Hazardous Pollutants), 2007). While Styrene has not formally been given a cancer risk rating, acute exposure has been linked to mucous membrane and eye irritation, and chronic exposure results in central nervous effects such as headache, fatigue, weakness, depression, and hearing loss (EPA (Hazardous Pollutants), 2007).

Biological microorganisms may cause infective or allergic building-related illnesses. In order for microorganisms to be virulent they must be viable (alive), which may be a factor of relative humidity, temperature, oxygen availability, pollutants, ozone, and ultra-violet light (ASHRAE, 2009, p. 10.7). Mold, fungi with a filament structure, produces spores (2 to 10 µm) that become airborne and may lead to a variety of health problems, such as headaches, breathing difficulties, skin irritation, allergic diseases, and aggravation of asthma symptoms. Microorganisms known to cause diseases in health-care facilities are *Legionella, Pseudomonas, Mycobacteria, Aspergillus, Fusarium, Cryptosporidium, Giardia*, and *Acanthamoeba*. *Legionellosis* is not rare, but is rarely reported or diagnosed. McCoy estimates in a study published in the ASHRAE Journal in 2006, that approximately 11 people per day die from *Legionella* in the United States (McCoy, 2006).

The final toxin and correlated health effects to be discussed is the radioactive gas, Radon. It is estimated that 21,000 people die in the United States from Radon caused lung cancer, making Radon the leading environmental cause of cancer and cancer related death. Smoking is still the leading cause of lung cancer, but Radon is second, and when the two are combined they have a synergistic effect (EPA (Radon), 2011). Most of the airborne hazards discussed in the sections above including most chemical and biological hazards can be filtered or prevented. Radon cannot be prevented, as it is a natural material that exists in soil. Therefore, it must be prevented from entering structures. Once it has found a way into a home, only dilution with ventilation can keep concentrations low enough to be non-toxic. Since Radon is colorless and odorless it is undetectable without proper instrumentation. Therefore the U.S. Environmental Protection Agency has initiated a program of testing and mitigation primarily for low-income and middle-income homes.

ASHRAE standards and guidelines focus on isolating a toxin and directly ventilating it (such as with vent hoods), general ventilation (the replacement of indoor air with outdoor air), prevention (regulations such as prohibiting smoking indoors), and air cleaning (using filters). While this may appear to be a comprehensive air quality approach, subsequent sections in this paper will propose an approach that adds an important component to this list. The integration of whole-system thinking, where waste is seen as the fuel for another process allows design for high indoor air quality, to also become an energy-efficient process.

CAIRO AS A CASE STUDY

Cairo, Egypt was selected as the research site due to its' large population coupled with severe outdoor air quality events such as the *black cloud*. The black cloud is caused by a number of factors. After the harvest season, agricultural waste is burned agricultural waste, primarily rice straw, in the Nile Delta region. The smoke and aerosols from these burns flow over metropolitan Cairo in a matter of hours. Since most of the burning happens at night, there is an inversion layer of warm air trapped close to the earth's surface that prevents the smoke from quickly dissipating into the outer atmosphere, thereby trapping the smoke close to the earth's surface (Marey, Gille, El-Askary, Shalaby, & El-Raey, 2012). The causes of the black cloud are not all local however, and are not all anthropogenic. Desert dust is also transported at high-altitudes (2.5 to 6 km) from the Western Sahara to the Nile Delta region by dust storms fueled by wind (Prasad, El-Askaray, & Kafatos, 2010).

There are three components to Cairo's aerosol chemistry: a background aerosol produced by daily traffic and industry, pollution produced by the burning of agricultural waste, and coarse desert dust. Due to weather effects, these components are amplified toward the end of July through winter. Aerosol particles can affect the radiation budget and temperature by changing the balance between solar and terrestrial radiation in the atmosphere – dust increases the absorption of solar radiation and modifies the scattering of sunlight. This blend of scales and types of aerosols leads to a heating of the atmosphere (El-Metwally, Alfaro, Abdel Wahab, Favez, Mohamed, & Chatenet, 2011). Figure 2 graphically indicates the general correlation with air temperature rising and aerosol concentration increase. As the white curve moves higher, there is a similar increase in dry-bulb temperature as shown when the color indicators tend toward yellow, orange, and red. The highest concentrations of aerosols were measured roughly between days 200 and 275 of the year – or the middle of July to the beginning of October – the time of year when agricultural burning takes place, Saharan dust blows toward the Nile Delta, and the inversion layer keeps source pollutants at low altitudes.

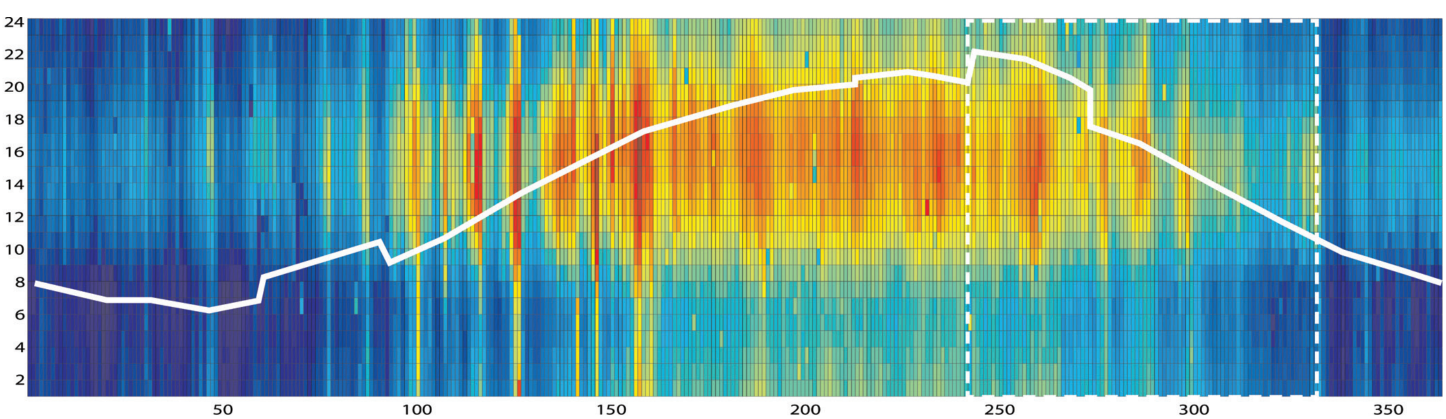

Figure 2. P-color plot of Cairo's dry-bulb temperature with optical aerosol depth overlaid in white

As previously explained, the customary way of improving indoor air quality is to ventilate the indoors with outside air. Given what the citizens of Cairo are suffering from outdoors, it is not logical to bring this air into homes without substantial pre-filtration. Most buildings in Cairo are not mechanically ventilated, and therefore the only means of ventilation is to open the window. With concentrations of particulate matter ten times higher than the World Health Organization (WHO) recommended limits, and Nitrogen oxide concentrations 150 percent higher than the WHO recommended maximum, it is not only inappropriate, but also potentially very harmful to use Cairo's outside air as a means of diluting indoor toxins.

MODULAR FILTRATION

A team of undergraduate students from Rensselaer Polytechnic Institute, Kyleen Hoover, Kateri Knapp, and James Wisneiwski, partnered with Carmen Trudell to design a modular filtration system capable of addressing Cairo's air quality challenges, while also being conscientious of energy efficiency, waste efficiency, and beauty. Initial design ideas were generated at the Center for Architecture, Science, and Ecology (CASE) under the direction of Anna Dyson, Jason Vollen, Ted Ngai, Reese Campbell, and Demetrios Comodromos. CASE is a joint venture between the architecture department at RPI and SOM, and is located at SOM's New York City office. Subsequent design refinement, module prototyping and testing is taking place at California Polytechnic State University in San Luis Obispo where the author is now an assistant professor.

The team invented a three-stage filtration process where different wall configurations would target various size air toxins. Together, these three filters are able to trap particles that are inhalable and smaller, as illustrated in Figure 1. The first filter, called the Cyclone Filter (Figure 3), targets large particles greater than 10 microns, or those primarily generated by the Saharan Desert dust storms. The second filter, called the Bio Filter (Figure 4), remediates smaller particles and gasses, including aerosols generated by combustion processes such as burning biomass and vehicle engines. The third filter (Figure 5), the Thermal Regulator, controls the condition of the air – in this case the temperature and relative humidity. This three-part modular filtration system is designed primarily for residential construction applications in lieu of traditional concrete block. The three filters are meant to work in sequence, so that larger particulates are removed first in a completely passive process. The smaller gasses and particles are removed next through a hybrid active/passive system, and then the third filter type accomplishes air conditioning or heating. The modules are essentially filtration walls, where air is intentionally passed through the wall in order to change the character of the air.

The Cyclone Filter works off of a well-known air-cleaning method that is commonly used in woodshop ventilation systems to remove sawdust from the air, and is also the basis for the Dyson vacuum cleaners. In a reverse-flow cyclone, air is spun in progressively tighter and tighter radii causing the air to move faster and faster. With this increase in velocity, heavier particulates will separate from the air due to centrifugal forces. These larger particles will be drawn through an opening in the bottom of the cyclone chamber into a hopper due to gravitational forces. The filtered air will decrease in density (increase in buoyancy) as it increases in velocity and will exit the cyclone chamber through an opening in the top (Vincent, 1995). While this method of air filtration has been widely used in industrial hygiene applications it has not been applied to an integrated architectural component.

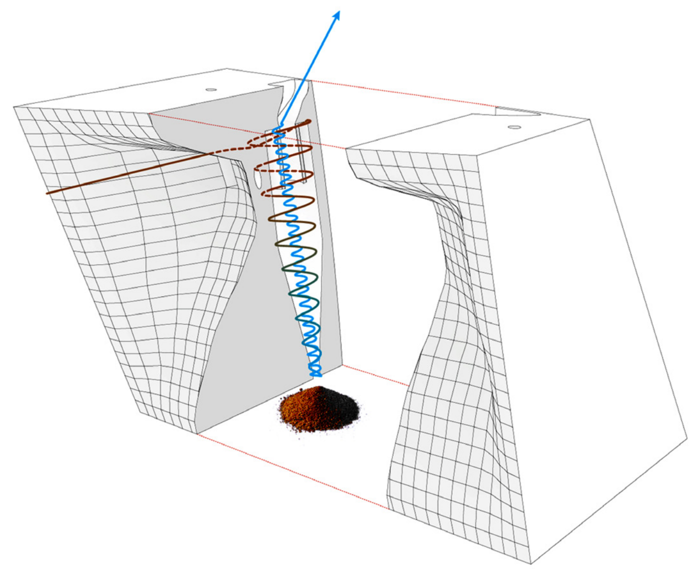

Figure 3. The cyclone filter showing dirty air entering from the left, spiraling down the filter where large particulates are dropped out, and then partially cleaned air escapes out the top of the module

By appropriating this industrial hygiene technology into a simple passive masonry wall, the locomotive force of wind, and the pressure difference between the windward and leeward sides of a wall can bring partially cleaned outdoor Cairo air into a private exterior space. The first filter is meant as a pre-filter. The resulting air is not of high enough quality to be used as indoor air yet, but this partially filtered air would be dramatically improved over exterior air conditions found in Cairo, and would therefore be better for people even in these private outdoor spaces. The process of bringing air through the porous modules of the masonry wall, will effectively remove large particulates so that the air inside of the courtyard will no longer be laden with dust. The twisted form of each masonry module allows for staggered stacking of the modules for alignment of internal waste pipes. Captured dirt and dust will be carried through these waste pipes to a storage basin at the base of the masonry wall. The storage basin would have an access hatch so that it may be periodically swept as a means of maintenance. This puts burden on the house occupants to keep this hopper free of excess dirt to ensure that the units continue to function properly and do not become clogged, and also puts the burden on them to properly discard the waste in a method that simply does not allow it become air entrained again. The partially cleaned air would exit the top of each module freely. This partially cleaned exterior air will be further filtered prior to entering the dwelling.

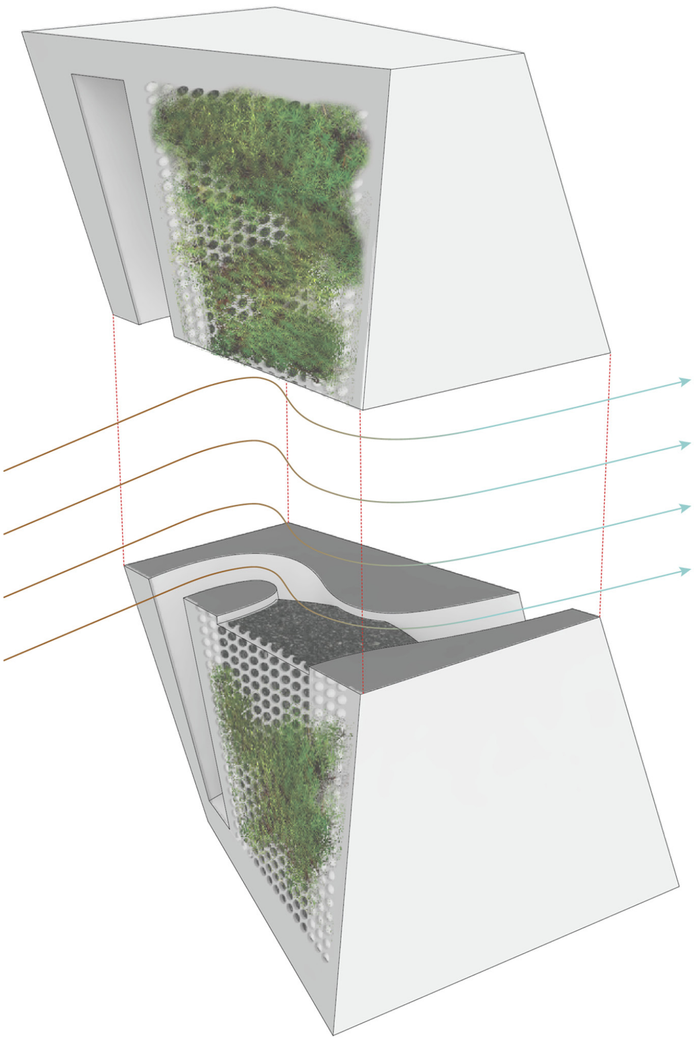

Figure 4. The biological filter uses phytoremediation principles to sequester and remediate toxins. Activated carbon acts as the filtration medium, while microorganisms in the plant root rhizosphere digest unwanted toxins.

The Biological Filter uses the principle of phytoremediation to naturally sequester and inoculate harmful gasses and particles below 2.5 microns in diameter. Biological methods for improving air quality have been well tested and documented first by NASA scientist B.C. Wolverton, and more recently as the Nedlaw Living Wall System, and the BI-AMPS System designed by CASE. A phytoremediation system relies on a balanced ecological approach to air filtration, where the waste of one process becomes the food source for the next. Almost all of the phytoremediation systems listed above rely on plants, a growing medium, activated carbon, a watering system and an air circulation system to adequately removed harmful toxins from air. Activated carbon is a critical component, as it sequesters small particulates and gasses. Once trapped, these harmful substances are then transformed into non-toxic elements by the microorganisms that are integral to the survival of the plant. These microorganisms live in the root area of the plant, and are capable of literally digesting the harmful toxins and excreting a waste product that may provide nutrition to the plant.

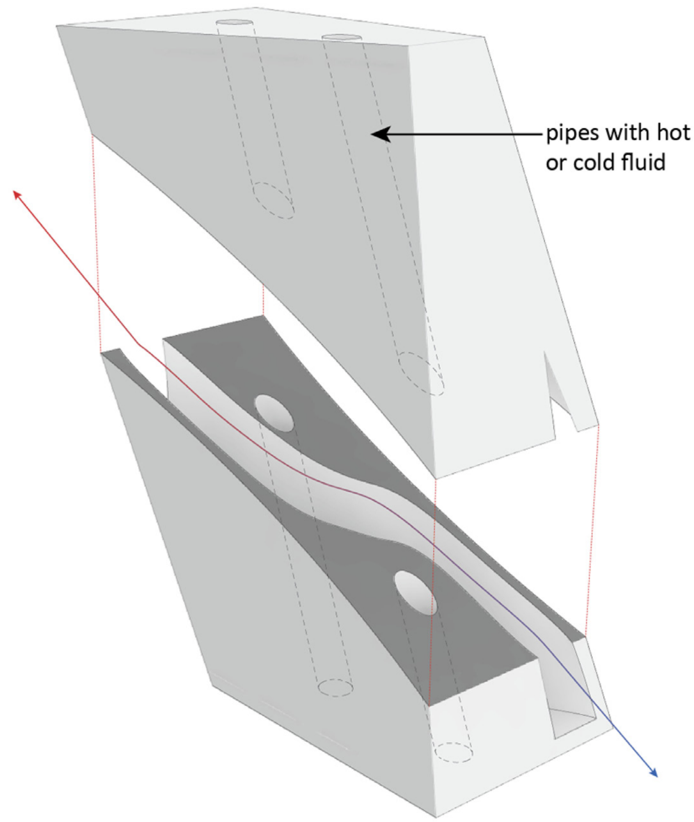

Figure 5. The thermal regulator controls air temperature through radiant heating or cooling.

The Thermal Regulator is not a filter in the same sense as the previous two filters. The Thermal Regulator does not improve the *content* of the air by removing unwanted toxins. The Thermal Regulator does however improve the *condition* of the air – in that it improves human comfort by addressing air temperature. The Thermal Regulator is a radiant heating and cooling system where the actual mass of the wall is used to transfer heat to or from air as it passes through voids in the wall. These voids are designed to be somewhat circuitous to increase the amount of time the air is in contact with the temperate wall surface. The wall works in a similar way as a radiant concrete floor heating system in that pipes of heated or chilled water are embedded in the volume of the concrete. The Thermal Regulator differs from a standard radiant concrete floor because in the Thermal Regulator, the air that is being conditioned chicanes through the labyrinthine pathways within the walls' girth. In standard radiant flooring, the natural convection effect of rising hot air drives the process. The three filters work together to provide complete *indoor environmental* *quality* address both the air condition and air quality parameters. While passive ventilation principles are favored, especially for single-family homes in a developing nation with an arid climate, active thermal comfort is incorporated into the Thermal Regulator, and fans that improve ventilation through the other filters could be incorporated for improved performance consistency. In addition to active and passive environmental control, this design also incorporates biological remediation. It should be understood that in order to address complex interior issues, such as the quality of the environment, it takes a holistic approach that is open to natural, man made, and living energy forms to adequately address the myriad of variables in-play.

THE IAQ BENEFITS OF PREFABRICATION

Building materials are a significant source of indoor air pollution. For many materials, such as paints and adhesives, the toxicity of the material deteriorates over a short period of time. For other materials, such as many plastics, they will continue to off-gas over their lifespan. For this reason, it is critical that all designers carefully specify materials and procedures that protect the health of construction workers and building occupants. One of the motivating forces behind designing a modular indoor air quality remediating system is that the modules can be made off-site in a controlled environment allowing any aerosolized waste to also be controlled. The modules can then be easily shipped using simple methods, often palletized, shared with many other masonry products.

In addition to the ease of fabricating off-site and transporting to the site, the modular system can be installed by hand, without the use of additional equipment that may contribute to mobile combustion source toxins. In future work, fabrication and testing of these modules will be carried out to optimize the form in order to create reliable high-performing filters that could rival the ability of standard HEPA filters. The desire is to fabricate the modular filters out of non-toxic ceramics to prevent the introduction of harmful gasses or particulates from entering the air. A vocabulary of pre-fabricated parts allowing for corners and other transitions would also be necessary in order to alleviate the need for on-site cutting – effectively preventing another source of on-site air pollution.

A structural benefit of constructing a modular comprehensive air quality remediation system is that the modular system itself can be the building structure, the air cleaning, and the air conditioning system all in one. This leads to material efficiency, energy efficiency in production and assembly, and simplicity in design. It also means that the air-cleaning portions of the building will never standalone as devices that can be abandoned or neglected. As an integral part of the structure and the building finish, the environmental control system is never secondary. This is also why it is so critical to rely as much as possible on low-energy and reliable motivating forces, such as the wind and such as the basic geometries that allow for separation.

REFERENCES

ASHRAE. *2009 ASHRAE Handbook -- Fundamentals* (SI). Atlanta, GA: American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc., 2009.

ASHRAE Special Project 200. “Indoor Air Quality Guide: Best Practices for Design, Construction, and Commissioning.” American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc., Atlanta, 2009.

Corsi, R L, A Karamalegos, H Simon, and G C Morrison. “Personal reactive clouds: Introducing the concept of near-head chemistry.” *Atmospheric Environment* (Elsevier) 41 (2007): 3161-3165.

El-Metwally, M., S C Alfaro, M M Abdel Wahab, O Favez, Z Mohamed, and B Chatenet. “Aerosol properties and associated radiative effects over Cairo (Egypt).” *Atmospheric Research* (Elsevier) 99, no. 2 (February 2011): 262-276.

EPA (Hazardous Pollutants). H*ealth Effects Notebook for Hazardous Air Pollutants.* November 2007. http://www.epa.gov/airtoxics/hlthef/hapindex.html (accessed June 19, 2012).

EPA (Radon). “Protecting People and Families from Radon: A Federal Action Plan for Saving Lives.” 2011.

EPA. *Volume I: Federal Programs Addressing Indoor Air Quality*. Report to Congress on Indoor Air Quality, Indoor Air Division, Office of Atmospheric and Indoor Air Programs, Office of Air and Radiation, Office of Research and Development, Washington DC: U.S. EPA, 1989.

Marey, Heba S, John C Gille, Hesham M El-Askary, Elsayed A Shalaby, and Mohamed E El-Raey. “Study of the formation of the “black cloud” and its dynamics over Cairo, Egypt using MODIS and MISR sensors.” *Journal of Geophysical Research: Atmospheres* (American Geophysical Union) 115 (November 2012).

McCoy, W F. “Legionellosis: Why the problem continues.” *ASHRAE Journal,* 2006: 24-27.

McDonough, William, and Michael Braungart. *Cradle to Cradle: Remaking the Way We Make Things*. New York, NY: North Point Press, 2001.

Molhave, L, B Bach, and O F Pedersen. “Human reactions to low concentrations of volatile organic compounds.” *Environment International* (Elsevier) 12, no. 1-4 (1986): 167-175.

Prasad, Anup K, Hesham El-Askaray, and Menas Kafatos. “Implications of high-altitude desert dust transport from Western Sahara to Nile Delta during biomass burning season.” *Environmental Pollution* (Elsevier) 158, no. 11 (November 2010): 3385-3391.

Vincent, James H. *Aerosol Science for Industrial Hygienists*. Tarrytown, NY: Elsevier Science Incorporated, 1995.

Wolverton, B C, and Takenaka Kozaburo. *Plants: Why You Can’t Live Without Them.* New Delhi: Luster Press | Roli Books, 2010.

Wolverton, B C, Anne Johhnson, and Keith Bounds. *Interior Landscape Plants for Indoor Air Pollution Abatement.* NASA and Sverdrup Technology, Inc., 1989.

World Health Organization. “WHO Guidelines for Indoor Air Quality: Dampness and Mould.” Regional Office for Europe, Copenhagen, Denmark, 2009.