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Phytoremediation of Indoor Air: NASA, Bill Wolverton, and the Development of an Industry

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Indoor air pollutants are a source of serious illnesses, including asthma, cancer, reproductive and neurological disorders. A 2002 World Health Organization Report attributes more than 1.6 million deaths a year--3 deaths a minute--to complications resulting from indoor air pollution.[1] Volatile Organic Compounds (VOCs) are emitted from the materials used to construct the buildings[2], the floor and wall coverings used to protect the buildings[3], the furnishings used to decorate the interiors[4], and the electronics and appliances that are used daily[5].

The problems associated with indoor air quality began to develop following the oil embargo of the 1970's, and regulations to increase the energy efficiency of buildings were enacted. The reduction in ventilation with outside air due to tighter seals, energy efficient glass, and lower air exchange rates resulted in the accumulation of VOCs, microorganisms, and particulates. The term "Sick Building Syndrome" entered common usage.

In 1988, the U.S. Environmental Protection Agency (US EPA) conducted a survey of air quality in public buildings and identified more than 900 VOCs in office buildings, nursing homes, hospitals and schools[6]. Of these VOCs, many were found in concentrations known to pose serious acute and chronic health risks. These included such compounds as benzene, ethylbenzene, xylene, styrene, trichlorethyhlene, decane, formaldehyde, 1,1,1-trichloroethane, dichlorobenzene and ethyl toluene[7].

Solvents in glues, paints and varnishes commonly used in the production of carpets, drywall and pressed wood furniture, such as toluene and formaldehyde were omnipresent. Over 40 VOCs have been identified that come from modern appliances such as computers, monitors and televisions[8]. The insidious effects of indoor air pollution have been associated with a 74% increase in asthma between 1980 and 1994 and children under the age of 5 in the United States have experienced an increase of 160 percent[9]. Epidemiological studies suggest this increase is at least partially attributable to reduced ventilation and increased energy efficiency in modern buildings[10]. The problem is not limited to the United States. There has been a 5 fold increase in Taiwan over 20 years; and a 30 fold increase in asthma patients in medical facilities in Japan over 30 years. Fifteen percent of the population of Australia, New Zealand and the Pacific Islands suffer from asthma as well. Indoor air pollution has been linked to increased prevalence of Parkinson's disease, brain tumors, multiple chemical sensitivity and other nervous system disorders.[11]

It was during this period of the early 1970's and 1980's when the issues associated with Sick Building Syndrome were gaining attention that the United States National Aeronautics and Space Administration (NASA) became an unlikely leader in identifying biological solutions to the problem of poor indoor air quality. NASA had been supporting work using biological systems

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for atmospheric regeneration since the 1950's, with the emphasis on using photosynthetic systems for the removal of carbon dioxide and regeneration of oxygen as part of a life support system[12]. The then Soviet Union was conducting tests using algae systems in the BIO-1 program (1964-1968) to regenerate the air at the Siberian Branch of the Soviet Academy of Sciences in Krasnoyarsk (Later renamed the Institute of Biophysics). These tests were expanded to include the use of higher plants in the BIOS-2 testing in the 1970's, and humans during BIO-3 in the 1980's[13]. Within NASA, large scale testing of bioregenerative life support systems was conducted in the Biomass Production Chamber (BPC) at Kennedy Space Center, Florida as part of the Controlled Ecological Life Support Systems (CELSS) Breadboard project.[14] However, the use of higher plants for cleaning the air did not evolve directly from these programs, but rather from the unlikely source at NASA's Mississippi Test Facility in Hancock County, Mississippi.

NASA had spectacular success with the development of the Mercury, Gemini and Apollo Programs that culminated in the Moon landings. The Mississippi Test Facility had been crucial in the development and testing of the rocket engines that propelled the Saturn V rockets into orbit. When the Apollo program ended, and the end of production of the Saturn V rockets, there was a dramatic decrease in funding to NASA and the future of the Mississippi Test Facility was in doubt. Jackson Balch, NASA Center Director, seized this period of uncertainty, and established an Applications Engineering Office to actively operate in a "marketplace" of science and develop a synergism in research that could cross bureaucratic, governmental, and disciplinary lines[15]. Director Balch then set out to find people to implement this strategy.

Bill Wolverton had became known to Director Balch three years earlier during a presentation Bill made at WinRock Farms, Arkansas on his finding that aquatic plants were capable of absorbing Agent Orange (mixture of 2,4,5-T,and 2,4 D) and organophosphate insecticides, used extensively during the Vietnam war[16]. Director Balch believed that practical application of environmental science would be critical to the continued operation of the test facility, and he was convinced Bill Wolverton's background was ideal for this new role.

Bill Wolverton was born in rural Mississippi in 1932 at the peak of the Great Depression, was raised in Mississippi, graduated high school and then served in the United States Air Force during the Korean Conflict. After leaving active service, he remained in the Air National Guard, and began his college education. He was awarded a Bachelor of Science Degree in Chemistry from Mississippi College in 1960, conducted graduate research on multiple myeloma and rheumatoid arthritis in the department of Microbiology and Biochemistry at the University of Mississippi Medical Center in Jackson, MS. He then accepted a position as a civilian scientist at the Naval Weapons Laboratory in Dahlgren, VA as head of the Chemical/Biological Branch Laboratory where he researched methods for protection of military personnel from chemical and biological warfare.

In 1965 he was transferred a bit closer to home at Eglin Air Force Base in the panhandle of Florida. There he continued his work on the protection from and decontamination of, chemical warfare agents, especially organophosphate agents, including VX gas, Sarin and Mustard gas. His and his research resulted in multiple patents.[17,18,19] While working at Eglin Air Force Base, he resumed graduate studies and focused on marine biology at the University of West Florida, Pensacola, Florida.

In 1971, Director Balch and Henry Auter, Director of Applications Engineering, recruited Bill Wolverton away from Eglin Air Force Station to head the Environmental Research Laboratory at NASA's Mississippi Test Facility. The primary objectives of the Environmental Research Laboratory were to 1) Research the environment's natural abilities to cleanse itself; 2) Research a closed ecological life support system for long-term space habitation; and 3) Provide usable Spin-off technologies to the American public.[20]

Upon assuming the position as head of the Environmental Research Lab, it became clear that the immediate need was to demonstrate the relevancy of environmental research to NASA. Bill Wolverton requested, and received, support from Director Balch to develop a constructed wetlands on the site in order to remove the toxic wastes that were accumulating in the environment though years of test firing of rocket engines. This investment paid immediate dividends, and the constructed wetlands are still functioning today. The value of this work to NASA was summarized below:

> *"Before Wolverton began his research at the MTF in 1971, government and private entities paid large sums of money trying to eradicate the plants[21]. Through the plant program, however, the hyacinth became useful as a natural resource, cleaning domestic and laboratory waste water with its large root system resembling octopus tentacles. Wolverton and McDonald used the plants, which produce beautiful lavender blossoms to clean all waste generated at the NSTL, including laboratory waste containing chemicals and heavy metals.*
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> *In the final analysis, the plant program saved the government more than $1 million up front, and millions more for operations and maintenance will be saved over the years. Wolverton gained worldwide recognition for the Vascular Aquatic Plant program. Newsmen, from Germany, England, Japan, and many other countries, visited the NSTL[22] in order to obtain the plant program story for their viewers. Wolverton and the aquatic plant program were also featured on major American television networks, such as NBC and CNN. In addition, Wolverton assisted with designing and installing similar waste treatment systems in Coral Springs, Disney World, Florida; Hercules, and San Diego, California; and Rio Hondo, Texas."*[23]

Although NASA's Apollo Program had ended, NASA's interest in human space flight had not. In the early 1970's NASA and the Soviet Union began cooperating in space, and three manned SkyLab Space station missions were conducted. During the SkyLab 3 mission, samples of the atmosphere were returned for analysis, and they yielded surprising results. There were over 300 VOCs detected in the SkyLab samples and 107 of those were identified in the crew compartments during manned missions. NASA immediately recognized that selection of materials low in the emission of toxic VOCs would be critical to maintaining the health of the crew. This recognition resulted in extensive off-gassing tests of any material used in spaceflight. Extensive in situ and post-flight monitoring of the spacecraft continues within NASA, and the range of VOCs from the most recent Space Shuttle and International Space Station Missions is publically available.[24]

Bill Wolverton had continued his studies with wetlands at the Institute for Advanced Studies, and obtained his Doctorate degree in environmental engineering in 1978. Following the SkyLab missions, Bill Wolverton and colleague, Rebecca McDonald, turned their attention to the problem of indoor air quality. They asked themselves whether plants could remove toxic chemicals from the air in the same manner that aquatic plants were removing toxins from the environment.

Bill approached the Center Director in 1980 for funding, and was provided a modest budget from the Center Director's Discretionary Funds to assess the ability of foliage plants to purify the air from energy efficient homes and future space stations. They choose to focus on formaldehyde, a VOC that was receiving considerable attention as an indoor pollutant at the time, due to its widespread use in pressed wood, and insulation used in the home and in house trailers. A small test chamber was built, and Golden Pothos (*Scindapsus aureus),* nephthytis (*Syngonium podophyllum)* and sweet potato (*Ipomoea batatas)* were tested for their ability to remove formaldehyde from the atmosphere. It was found that the concentration of VOC's could be reduced when common houseplants were introduced into the closed environment. This was a very important finding, and they began to further research plant removal of formaldehyde and other VOCs from the air.

These initial experiments were very encouraging, with all three species showing dramatic reductions in formaldehyde concentrations in the chambers over a 24 hour cycle. These results were first published as an internal NASA technical memorandum in 1982.[25] Additional testing was performed and the results of the NASA research were published in the Journal of Economic Botany in 1984[26]. One of the conclusions of the research was:

> "Based on the *Chlorophytum elatum* var. *vittatum* data, one spider plant in a 3.8 l (1 gal) pot can effect the removal of 31,220-62,440 µg CH_2O/6hr. To meet the air purification needs of the home just described, 8-15 spider plants (3.8 l pot size) would be need to purify the air continuously"[27].

NASA promoted the release of these findings, and the results were enthusiastically welcomed by the public. Dr. Wolverton continued these studies, and examined the ability of plants to remove combustion gases, which are the primary indoor pollutants for most of the developing world. These results were published in the Journal of the Mississippi Academy of Sciences in 1985.[28]

Realizing the value of these findings, the leaders of the interior plantscape industry approached Dr. Wolverton about additional funding for his research. As a result of these discussions, The Associated Landscape Contractors of America (ALCA, now known as the Professional Landcare Network) approached the senior management of the newly renamed John C. Stennis Space Center, about jointly funding a two year study to evaluate the effects of the most common houseplants in the industry on their ability to remove VOCs from the air.[29,30] The research concentrated on three of the most common VOCs: formaldehyde, benzene and trichloroethylene.

This work was revealing, in that it demonstrated that there were significant differences in the ability of different plants to remove airborne contaminants. These findings were compiled and the final report released. Based upon the public interest received from the 1984 article published in Economic Botany, Dr. Wolverton, the management of NASA Stennis Space Center, and the ALCA were anticipating an even stronger response from the public.

A strategy was developed whereby the final report, entitled "Interior Landscape Plants for Indoor Air Pollution Abatement" would be released during a press conference at the National Press Club in Washington D.C. in conjunction with "Plants for Clean Air Day" on Capitol Hill.[31] A not-for-profit organization, Plants for Clean Air Council, was established with Jan Roy as the director, to establish a national information campaign to promote the value of living plants in the home.[32] The report was subsequently published in InteriorScape Magazine.[33]

Following the release of the Final Report in September, 1989, there was a huge public interest in the "Top 12 Plants for Air Quality". Dr. Wolverton was immediately sought out for interviews on major TV networks, was interviewed by numerous newspapers and magazines, and promoted the value of interior plants on air quality at any opportunity. The Plants for Clean Air Council, initiated a public relations campaign as well, promoting the work of NASA and Dr. Wolverton at John C. Stennis Space Center.[34]

NASA funded research in closed environments for long duration space missions from the late 1970's. The Breadboard Project of the Controlled Ecological Life Support Systems (CELSS) program was being constructed at John F. Kennedy Space Center in Florida to test the feasibility of bioregenerative life support on a one person scale, large scale human test facilities were being designed at Lyndon B. Johnson Space Center in Texas, and the private enterprise Space Ventures was developing the Biosphere 2 project in Oracle, Arizona. These projects were focused on using plants for life support. These experiments monitored the production of VOC's[35],[36], but the primary research was directed towards the role of plants for life support[37].

In contrast, Dr. Wolverton, with the support of the management of Stennis Space Center, and backing of the ALCA, chose to scale up the research at Stennis to demonstrate the beneficial role of plants in closed life support systems to maintain a healthy living environment. The result was the construction of the Biohome constructed of synthetic materials and engineered for maximum closure of the air exchange and energy efficiency. The Biohome had two spaces: a 32 m^2 living area and a 27.5 m^2 bioregenerative area for reclamation of water and food[38]. The Biohome was constructed entirely of synthetic materials, highly insulated (R-40), and tightly sealed. Upon entering the facility, there were high concentrations of VOCs detected, and visitors exhibited symptoms of toxicity, including burning eyes, scratchy throat, trouble breathing and other classic symptoms of sick building syndrome.

A number of low-light tolerant foliage plants were placed into the 'Biohome' and the facility allowed to equilibrate for several days. The striking result was that the symptoms of runny eyes were no longer exhibited, and GC/MS analysis confirmed the reduction of VOCs in the atmosphere. In order to develop a case study for habitation, a graduate student lived in the chamber for the summer, with no negative health effects observed. An important finding in the study revealed that plants are most effective in removing VOCs in non-ventilated, energy-efficient buildings[39].

Upon the completion of its research role, the "BioHome" was moved from the Environmental Research Laboratory to the Stennis Visitor Center and renamed "One Mainstreet Mars", where it continued to serve an educational role on the value of interior plants. The facility was destroyed in 2005 when Hurricane Katrina made landfall along the Mississippi coastline[40].

In 1990, following the release of the final report of the research on interior plants, Dr. Wolverton retired from NASA and started a small research company, Wolverton Environmental Services, with his wife, Yvonne, and son, John. Prior to his retirement, Dr. Wolverton received many awards from NASA, including induction into the U.S. Space Foundations Hall of Fame in 1988. He was also invited to open the 1989 Aaslmeer Flowertrade Exhibition in the Netherlands, the first American to be awarded that honor.

Wolverton Environmental Services concentrated on obtaining additional data on the use of phytoremediation to address wastewater and indoor air pollution problems. To further demonstrate how interior plants could be used to purify and revitalize indoor air while treating raw sewage, he had such a system installed in a sunroom at his home in Picayune, Mississippi. This system worked successfully for seventeen years before he converted it back to a regular hydroculture plant growth system without raw sewage as the nutrients[41].

Since leaving NASA, Dr. Wolverton has continued to conduct research, supported the interior plant industry, lectured all over the world and published three books. His first book, *Eco-Friendly Houseplants* was published in the United Kingdom in 1996, then released the following year in the United States under the title *How to Grow Fresh Air.* This book has now been translated into 15 languages and provides the basic information for using plants to improve air quality the world over.

Dr. Wolverton served as the scientific spokesperson for the 'Plants for Clean Air Council, participating in campaigns to educate the public about the ability of interior plants to improve indoor air quality and to promote their health benefits. He has participated in publicity tours of most major cities, and is a frequent guest on television and radio shows and is regularly interviewed by newspapers and magazines. Dr. Wolverton has provided hundreds of lectures at professional associations such as the American Institute of Architects, landscape architect groups, universities, and local interiorscape associations.

Dr. Wolverton has helped shape public policy by providing testimony before the United States House of Representatives; Subcommittee on Agricultural Development, Food and Drug Administration and Related Services United States Senate; Committee on Environment and Public Works; Subcommittee on Toxic Substances, Environmental Oversight, Research and Development.

For over a decade Dr. Wolverton has also served as a consultant to Takenaka Garden Afforestation, the largest interiorscape company in Tokyo, where 'Ecology Gardens' are designed in hospitals to improve the psychological and physiological health of both patients and employees. The interior gardens are designed to complement the mind/body healing by including plants to improve air quality in a garden that is designed to improve healing and recovery.[42]

Research by Wolverton Environmental Services has found that increasing the flow of air through the root system increases the removal of VOCs significantly more than a single traditional potted plant. This discovery was patented[43], and he has teamed with a Japanese company, Actree Corporation, to develop what the Japanese firm is marketing as the EcoPlanter. Using high-efficiency carbon filters and a root-level circulation system, the pot allows the plant to remove approximately 200 times more VOCs than a single traditionally-potted plant can remove. In the U.S., a similar product is manufactured by U.S. Health Equipment Company under the trade name, Plant Air Purifier.[44]

Dr. Wolverton's most recent book *Plants: Why You Can't Live Without Them* written with Kozaburo Takenaka was published in 2010, and provides an overview of the development of the industry, from small chamber studies at NASA's Mississippi Test Facility (now NASA John C. Stennis Space Center) to the design of buildings encompassing living walls, atriums and interior landscaping. This book clearly shows the impact that NASA, Dr. Wolverton, and industry-backing, have made to the lives of millions around the world.

Dr. Wolverton's pioneering research at NASA's John C. Stennis Space Center has increased the public's awareness of the critical role of plants in the environment[45], stimulated debate on the role of interior plants for improving indoor air quality[46,47,48], expanded research on the role of many plants to improve air quality[49,50,51,52] and provided the foundation for a robust and expanding industry to incorporate living plants into buildings where we live and work[53,54].

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