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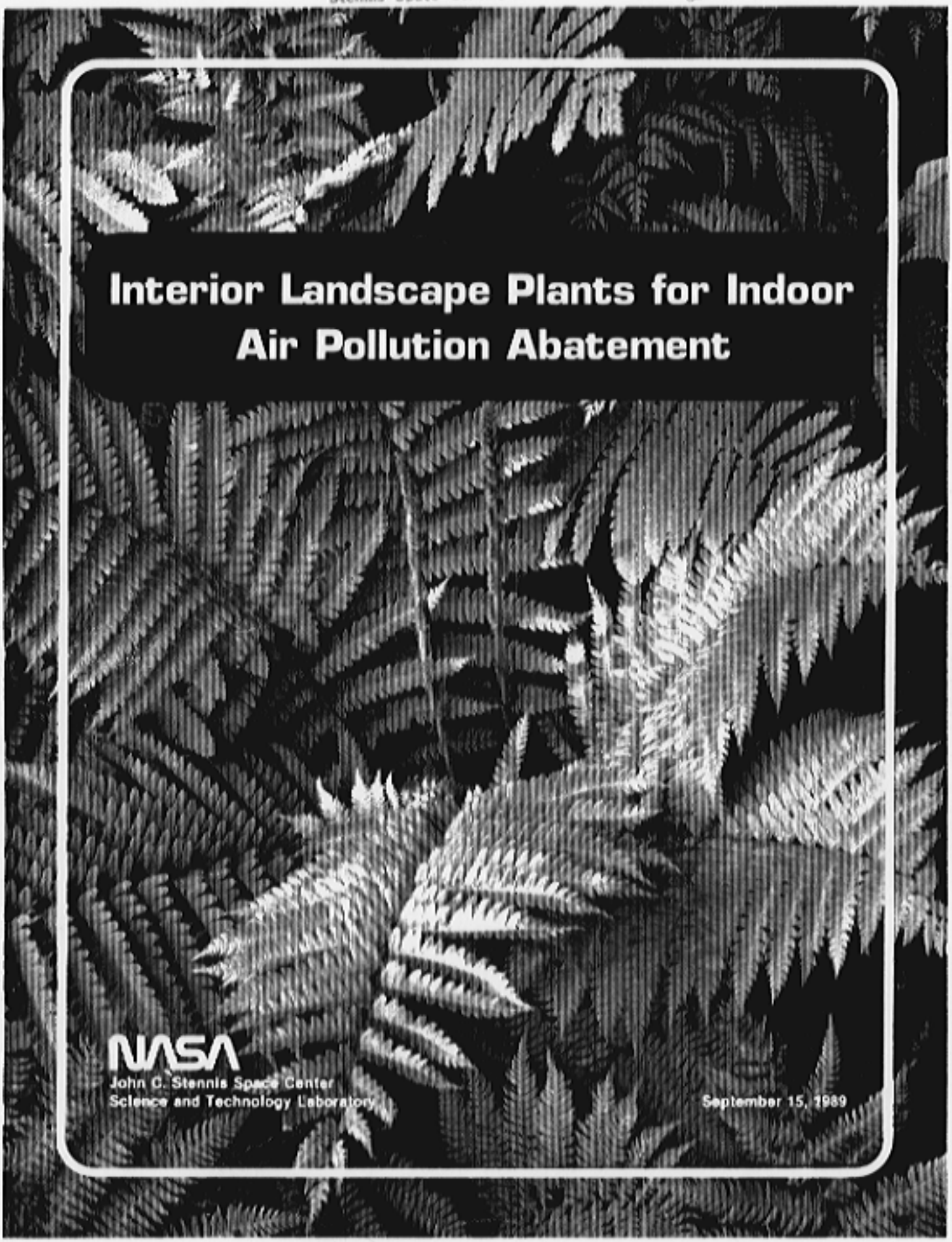

Interior Landscape Plants for Indoor Air Pollution Abatement

NASA
John C. Stennis Space Center
Science and Technology Laboratory

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INTERIOR LANDSCAPE PLANTS FOR INDOOR AIR POLLUTION ABATEMENT

FINAL REPORT—SEPTEMBER 15, 1989

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National Aeronautics and Space Administration
John C. Stennis Space Center
Science and Technology Laboratory
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ABBREVIATIONS AND ACRONYMS

Term	Definition
ALCA	Associated Landscape Contractors of America
EPA	Environmental Protection Agency
GC	gas chromatograph
HP	Hewlett-Packard
NASA	National Aeronautics and Space Administration
PCA	plate count agar
TCE	trichlorethylene
UF	urea formaldehyde
UFFI	urea-formaldehyde foam insulation
cfu/g	colony forming units per gram
cm	centimeter
cm^2	square centimeter
g	gram
h	hour
in.	inch
m	meter
mL	milliliter
min	minute
m^3	cubic meter
p/m	parts per million
s	second
yr	year
μL	microliter
°C	degrees Celsius

INTERIOR LANDSCAPE PLANTS FOR INDOOR AIR POLLUTION ABATEMENT

INTRODUCTION

During the late 1970s, when the energy crunch was being felt at both the gas pump and in heating and cooling costs, buildings were being designed to maximize energy efficiency to help alleviate spiraling energy costs. Two of the design changes that improved energy efficiency included superinsulation and reduced fresh air exchange. However, upon the occupation of these buildings, the workers began to complain of various health problems such as itchy eyes, skin rashes, drowsiness, respiratory and sinus congestion, headaches, and other allergy-related symptoms. It was determined that the airtight sealing of buildings contributed significantly to the workers' health problems. Similarly, synthetic building materials, which are known to emit or "off-gas" various organic compounds, have been linked to numerous health complaints. The office equipment and furnishings placed in these buildings are also a contributing factor because of the types of materials used in their manufacture and design.

Man himself should be considered another source of indoor air pollution, especially when living in a closed, poorly ventilated area. This becomes very apparent when a large number of people are present in a confined place such as an airplane for an extended period of time.

All of these factors collectively contribute to a phenomenon called "sick building syndrome." One world health organization recently estimated that approximately 30 percent of all new or remodeled buildings have varying degrees of indoor air pollution. Problems of this type have been reported in the United States and Canada as well as in most other highly developed nations of the western world.

Two major problems with indoor air pollution are the identification of the trace chemicals and their correlation with diseaselike symptoms. Energy-efficient buildings that are filled with modern furnishings and high-tech equipment off-gas hundreds of volatile organics which possibly interact with each other. Even at concentrations below present detection limits, some of these chemicals and reactive byproducts may adversely affect inhabitants of these buildings. The problems of indoor air pollution have been studied and documented by many investigators over the past ten years.[1-27] Dr. Tony Pickering of the Wythenshawe Hospital near Manchester, England, has studied sick building syndrome extensively and has learned that symptoms are minimal in naturally ventilated buildings which contained the highest levels of microorganisms. On the other hand, the highest levels of symptoms are found in mechanically ventilated buildings containing low levels of microorganisms. The results of his analyses indicate that it is unlikely that symptoms associated with sick building syndrome can be attributed to microorganisms.

Now that most environmental scientists and government agencies agree that indoor air pollution is a realistic threat to human health, how can the problem be solved?

A PROMISING, ECONOMICAL SOLUTION TO INDOOR AIR POLLUTION

The first and most obvious step in reducing indoor air pollution is to reduce off-gassing from building materials and furnishings before they are allowed to be installed. The National Aeronautics Space Administration (NASA) identified indoor air pollution problems associated with sealed space habitats over 16 years ago.[1] Although a final solution to the trace contamination problems in these sealed environments has not been found, NASA does screen for off-gassing all new materials that are to be used in future space structures.

Another promising approach to further reducing trace levels of air pollutants inside future space habitats is the use of higher plants and their associated soil microorganisms.[28-29] Since man's existence on Earth depends upon a life support system involving an intricate relationship with plants and their associated microorganisms, it should be obvious that when he attempts to isolate himself in tightly sealed buildings away from this ecological system, problems will arise. Even without the existence of hundreds of synthetic organic chemicals off-gassing into tightly sealed environments, man's own waste products would cause indoor air pollution problems.

The answer to these problems is obvious. If man is to move into closed environments, on Earth or in space, he must take along nature's life support system. This is not easily achieved, however. At John C. Stennis Space Center, NASA has been attempting to solve this ecological puzzle for over 15 years. Professor Josef Gitelson of the USSR and his team of scientists and engineers have also been working with closed ecological systems for many years in Krasnoyarsk, Siberia.[30] Only recently, however, have critical parts of this complex puzzle begun to come together. Although maintaining the balance of the complete ecological cycle involves treating and recycling sewage, toxic chemicals, and other industrial water and air pollutants, only indoor air is addressed here.

In this study the leaves, roots, soil, and associated microorganisms of plants have been evaluated as a possible means of reducing indoor air pollutants. Additionally, a novel approach of using plant systems for removing high concentrations of indoor air pollutants such as cigarette smoke, organic solvents, and possibly radon has been designed from this work. This air filter design combines plants with an activated carbon filter as shown in Figure 1. The rationale for this design, which evolved from wastewater treatment studies, is based on moving large volumes of contaminated air through an activated carbon bed where smoke, organic chemicals, pathogenic microorganisms (if present), and possibly radon are absorbed by the carbon filter. Plant roots and their associated microorganisms then destroy the pathogenic viruses, bacteria, and the organic chemicals, eventually converting all of these air pollutants into new plant tissue.[31-37] It is believed that the decayed radon products would be taken up by the plant roots and retained in the plant tissue. Experiments are currently being conducted to test this hypothesis for NASA at the Department of Energy Oak Ridge National Laboratories in Oak Ridge, Tennessee.

As NASA looks toward the possibility of sealing people inside a Space Station, or moon base, along with large numbers of plants the ecology of such a closed environment (interactions

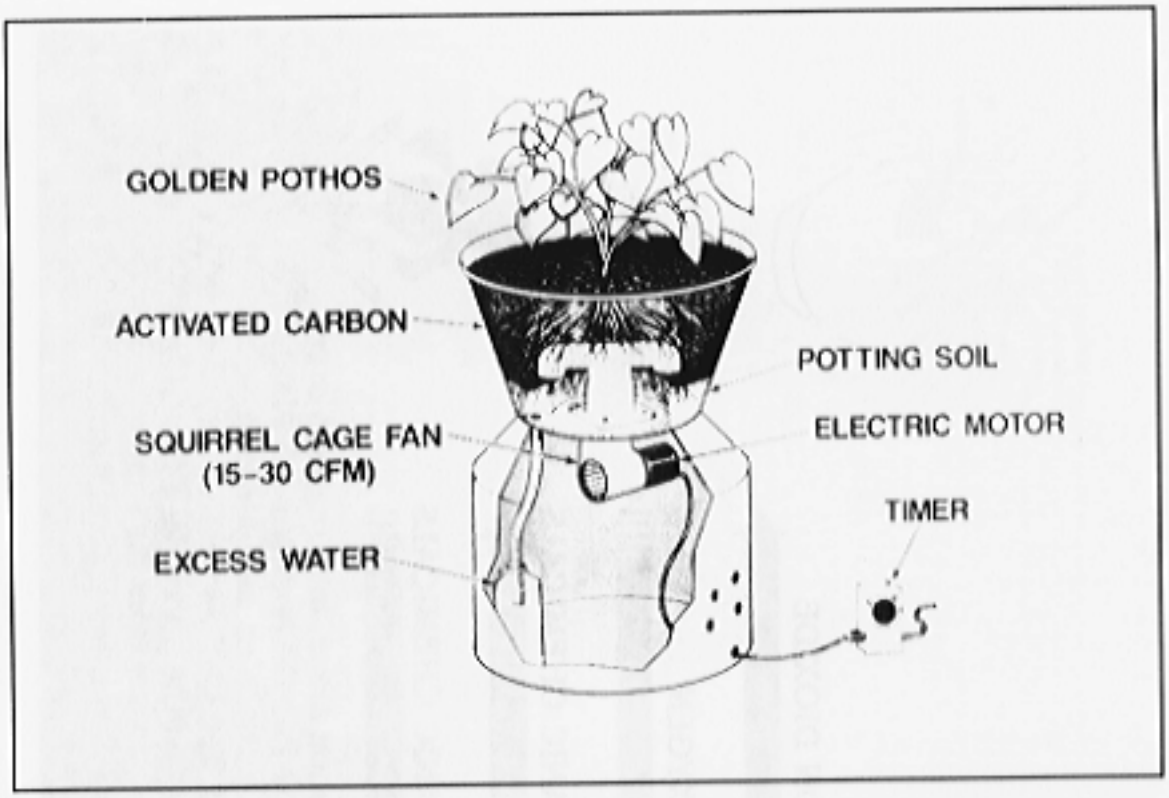

Figure 1. Indoor air purification system combining houseplants and activated carbon.

between man, plants, microorganisms, soil, etc.) must be further evaluated. See Figure 2. As plant studies continue at Stennis Space Center, emphasis is being placed not only on identifying trace chemical contamination, but also on identifying any volatile organic metabolites that may be off-gassed by plants themselves.

This joint effort between NASA and the Associated Landscape Contractors of America (ALCA) covers two years of data on the potential use of houseplants as a tool in solving indoor air pollution problems on Earth, and has gone a long way toward reminding man of his dependence on plants for his continued existence and well-being on our planet.

CHEMICALS USED IN THE PLANT SCREENING TESTS

Benzene

Benzene is a very commonly used solvent and is also present in many basic items including gasoline, inks, oils, paints plastics, and rubber. In addition, it is used in the manufacture of detergents, explosives, pharmaceuticals, and dyes.

Benzene has long been known to irritate the skin and eyes. Furthermore it has been shown to be mutagenic to bacterial cell cultures and has shown embryotoxic activity and carcinogenicity in some tests. Evidence also exists that benzene may be a contributing factor

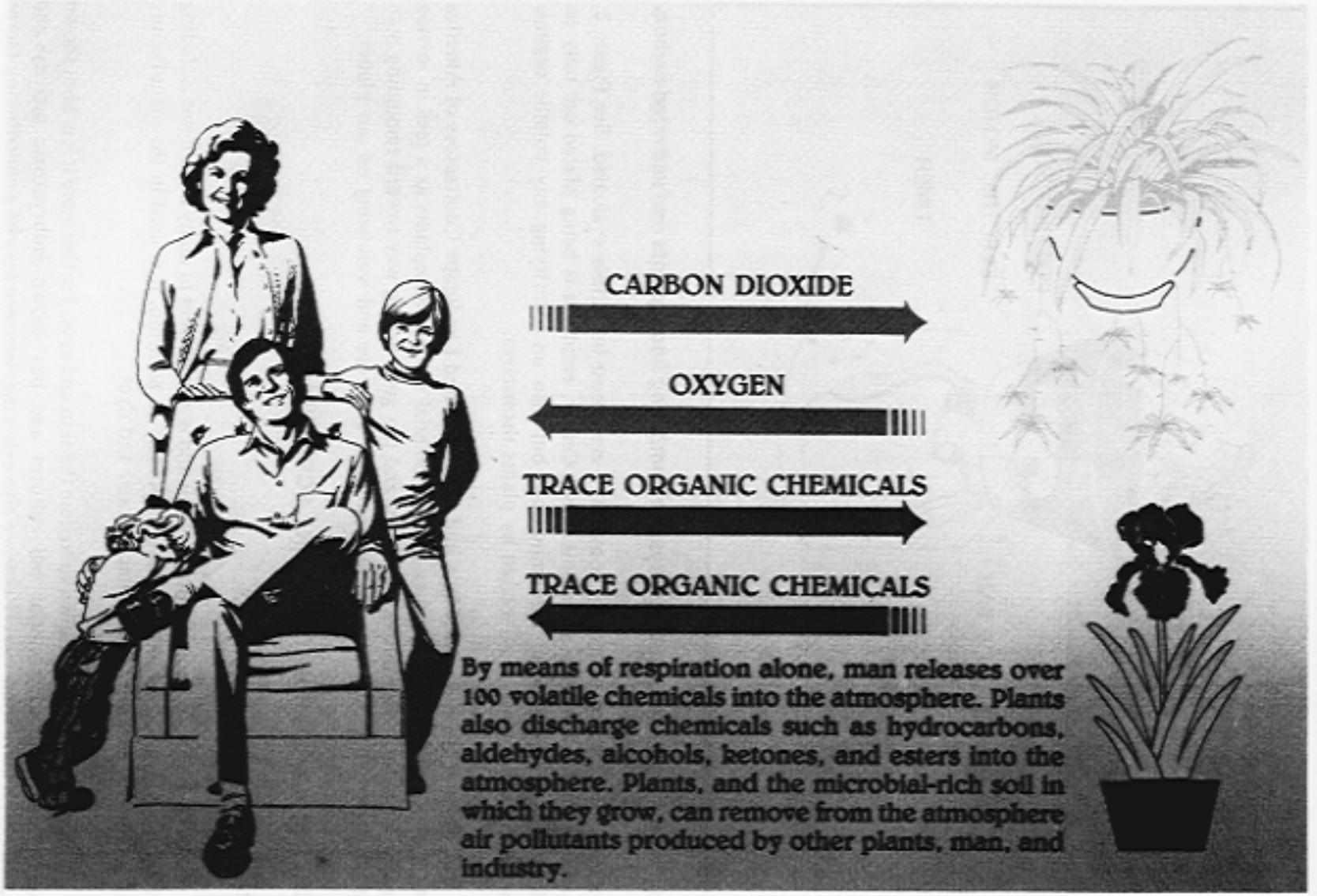

Figure 2. Man's interaction with his environment—plants, soil, microorganisms, and water.

to chromosomal aberrations and leukemia in humans. Repeated skin contact with benzene causes drying, inflammation, blistering, and dermatitis. Acute inhalation of high levels of benzene has been reported to cause dizziness, weakness, euphoria, headache, nausea, blurred vision, respiratory diseases, tremors, irregular heartbeat, liver and kidney damage, paralysis, and unconsciousness. In animal tests, inhalation of benzene led to cataract formation and diseases of the blood and lymphatic systems. Chronic exposure to even relatively low levels causes headaches, loss of appetite, drowsiness, nervousness, psychological disturbances, and diseases of the blood system, including anemia and bone marrow disease.

Trichloroethylene

Trichloroethylene (TCE) is a commercial product with a wide variety of industrial uses. Over 90 percent of the TCE produced is used in the metal degreasing and dry-cleaning industries, but it is also used in printing inks, paints, lacquers, varnishes, and adhesives. In 1975, the National Cancer Institute reported that an unusually high incidence of hepatocellular carcinomas was observed in mice given TCE by gastric intubation. The Institute considers this chemical a potent liver carcinogen.

Formaldehyde

Formaldehyde is a ubiquitous chemical found in virtually all indoor environments. The major sources, which have been reported and publicized, include urea-formaldehyde foam insulation (UFFI) and particle board or pressed-wood products. Consumer paper products, including grocery bags, waxed papers, facial tissues, and paper towels, are treated with urea-formaldehyde (UF) resins. Many common household cleaning agents contain formaldehyde. UF resins are used as stiffeners, wrinkle resisters, water repellants, fire retardants, and adhesive binders in floor covering, carpet backing, and permanent-press clothes. Other sources of formaldehyde include cigarette smoke and heating and cooking fuels such as natural gas and kerosene.

Formaldehyde irritates the mucous membranes of the eyes, nose, and throat. It is a highly reactive chemical that combines with protein and can cause allergic contact dermatitis. The most widely reported symptoms from exposure to high levels of this chemical include irritation of the upper respiratory tract and eyes and headaches.[2,3] Until recently, the most serious disease attributed to formaldehyde exposure was asthma. However, the Environmental Protection Agency (EPA) has recently conducted research which indicates that formaldehyde is strongly suspected of causing a rare type of throat cancer in long-term occupants of mobile homes.

MATERIALS AND METHODS

The following ALCA plants were screened:

Common Name	Scientific Name
Bamboo palm	*Chamaedorea seifritzii*
Chinese evergreen	*Aglaonema modestum*
English ivy	*Hedera helix*
Ficus	*Ficus benjamina*
Gerbera daisy	*Gerbera jamesonii*
Janet Craig	*Dracaena deremensis "Janet Craig"*
Marginata	*Dracaena marginata*
Mass cane/Corn cane	*Dracaena massangeana*
Mother-in-law's tongue	*Sansevieria laurentii*
Peace lily	*Spathiphyllum "Mauna Loa"*
Pot mum	*Chrysanthemum morifolium*
Warneckei	*Dracaena deremensis "Warneckei"*

All plants tested were obtained from nurseries in our local area. They were kept in their original pots and potting soil, just as they were received from the nursery, and were maintained in a greenhouse between tests. Stern's Miracle-Gro fertilizer was used to keep the plants in a healthy condition for the project.

Chemical contamination tests were conducted in four Plexiglas chambers, which were constructed to the following dimensions:

	Width*	Depth*	Height*
Two chambers measuring	0.76 (30)	0.76 (30)	0.76 (30)
Two larger chambers measuring	0.76 (30)	0.76 (30)	1.53 (60.5)

The tops of the small chambers and side sections of the large chambers were removed to allow entry. Bolts and wing-nuts ensured complete sealing of the lids and created airtight chambers for testing. Constant illumination was provided during the testing from a bank of Damar Gro-lights that encircled the outside of each chamber. Mounted on the inside of each chamber has a coil of copper tubing through which water at a temperature of 7 °C was circulated. This cooling coil prevented the Gro-lights from causing excessive heat buildup inside the chambers and minimized any fogging from plant respiration in the chambers. The chambers also contained two small removable ports, each 0.6 cm (1/4 in.) in diameter, through which contaminants could be introduced and air samples could be obtained. A small fan was used to circulate air within each chamber.

*Each dimension is given in meters (m); the equivalent in inches (in.) is given in parentheses.

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All tests were conducted for a period of 24 h. Experimental testing included sealing a selected plant in the Plexiglas chamber, injecting one of the three chemicals into the chamber in the method described below, and collecting air samples immediately following chemical introduction, at 6 h and, finally, 24 h later. Leak test controls, wherein the same chemicals were injected into an empty, sealed chamber, were conducted periodically throughout the study. In addition, soil controls without plants were tested to determine if the potting soil and associated microorganisms were effective in removing the different chemicals. These control tests were conducted by using pots of the same size containing the same potting soil as the potted plants used in actual testing. Experimental procedure then followed the same order as described above.

Benzene testing at high concentrations was performed by introducing 35 μL of benzene into the chamber using a 50 μL microsyringe. The benzene was injected onto a small metal tray attached to the chamber wall just below the introduction port and allowed to evaporate with the help of the fan inside the chamber. A period of 30 min was allowed for complete evaporation of the benzene prior to withdrawing the initial sample.

Sampling was done with a Sensidyne-Gastec air sampling pump and gas detector tubes specific for benzene concentrations ranging between 1 and 100 p/m. In sampling, a 200-mL volume of air from the chamber was drawn through a Gastec tube. Detection of a color change in the benzene-specific indicator reagent present in the tube measured the concentration of benzene.

Introduction and sampling of TCE was performed in a similar manner, except that the indicating reagent in the Gastec tubes was specific for TCE. The levels of TCE that could be detected ranged from 1 to 25 p/m.

Because formaldehyde is a water-soluble chemical and is routinely supplied as a 37.9 percent solution in water, it was necessary to utilize a different method to introduce this chemical into the test chambers. The formaldehyde solution was placed into a gas scrubber apparatus, which was attached to both an air pump and to the chamber sample inlet using pieces of Tygon tubing. Air was bubbled through the formaldehyde solution and introduced into the chamber as a gas. The time necessary to achieve the desired concentrations of formaldehyde in the two chambers was determined experimentally to be 50 s for the small chamber and 120 s for the large chamber. Sampling was performed in the same manner as that used for benzene and TCE using a Sensidyne-Gastec air pump and formaldehyde-specific tubes. The detection range of the formaldehyde-specific tubes was 2 to 20 p/m.

Because the Sensidyne-Gastec equipment was not sensitive enough for testing less than 1 p/m concentrations, a gas chromatographic method was developed for low-concentration analysis of benzene and TCE simultaneously in single sample. For the low-concentration benzene-TCE studies, two chambers of similar size were used, having volumes of 0.868 and 0.694 m^3. Benzene and TCE were introduced into the chambers using a 1-μL volume of an equal volume mixture of benzene and TCE. The sample was injected onto a Kimwipe tissue and allowed to evaporate for a 30-min period before the initial sampling. Sampling was performed by using the air pump to withdraw 200 mL of air through a glass tube containing

Tenax adsorbent. The samples were analyzed promptly using a Supelco air desorption unit interfaced to a Hewlett-Packard (HP) Model 5890 gas chromatograph (GC) equipped with an HP Ultra 2 capillary column and flame ionization detector.

GAS CHROMATOGRAPH-MASS SELECTIVE DETECTOR ANALYSIS FOR TRACE METABOLITES

After chemical injection, 500-mL air samples were collected from the chambers onto 18-cm (7-in.) by 0.6-cm (1/4-in.) outside diameter stainless steel tubes packed with Tenax adsorbent, using the Sensidyne-Gastec air pump. Trace chemical contaminants were desorbed from the Tenax tubes using a Tekmar Model 5000 automatic desorber into a HP 5890 GC equipped with a 30-m, 0.32 mm inside diameter, Restek Rt_X—volatiles capillary column. The GC oven was initially cooled to 0 °C using carbon dioxide, and then followed a temperature program beginning at 0 °C, with a 30-s hold at 0 °C, and a rise in temperature of 8 °C/min. The program ended when the temperature reached 200 °C, for a total run time of 25.5 min. After separation on the GC, the sample entered an HP 5970 mass selective detector. Analysis of the sample was conducted using a scanning range of 35 to 400 atomic mass units.

MICROBIOLOGICAL ANALYSIS

Using both potted plants and potting soil controls, 1-g samples of soil were taken from surface and subsurface regions (approximately 10 cm in depth). Samples were subsequently analyzed by means of the pour plate technique to determine the number of "colony forming units" per gram of sample (cfu/g). Plate count agar (PCA) was utilized as the primary microbiological medium. Plate count data reflect bacteriological counts.

Triplicate samples were taken both before and after exposure of the plants and soil to benzene and TCE. Following incubation at 25 °C for 24 h, samples were examined for the presence of bacteria. Due to the inherently slower growth rate of fungi and actinomycetes, these microorganisms cannot be detected until three to five days of incubation have elapsed. After plate count data were recorded, both bacterial and fungal samples were isolated. Stock cultures were maintained on PCA and Sabouraud's dextrose agar, respectively. Bacterial isolates were then subjected to a series of biochemical tests in order to aid in preliminary identification. Fungal isolates were examined by light microscopy to search for the presence of asexual and sexual spores.

ACTIVATED CARBON-HOUSEPLANT AIR FILTER SYSTEM

Air filters designed as shown in Figure 1 were tested in one of the large Plexiglas chambers for simultaneous removal of benzene and TCE. Benzene and TCE in 500 μL volumes were injected onto a Kimwipe tissue taped inside the chamber and were allowed to evaporate for 5-min. Complete volatilization occurred and 100-mL air samples were drawn, using a Tenax tube and air pump. Analysis followed on the Supelco desorber and HP GC that have been previously described. Samples were drawn initially and at 15-min intervals for a minimum of 2 h, or until all trace chemicals were removed.

RESULTS AND DISCUSSION

The ability of houseplants or potting soil to remove benzene, TCE, and formaldehyde from sealed experimental chambers is demonstrated in Tables 1 through 8. The screening of plants shown in Tables 1 through 3 was accomplished during the first year of studies, while data shown in Tables 4 through 8 were collected during the second and final year of this project.

Plants in Tables 1 through 4 were exposed to high concentrations of chemicals, in the 15 to 20 p/m range. Although these exposures gave a good indication of which plants might be particularly suited to the removal of one or more of these chemicals, they are far above the levels commonly found in indoor atmospheres. During the final year of this project, investigations were conducted using low concentrations of benzene and TCE (less than 1 p/m) and more sophisticated analytical methods. Results from these studies are shown in Tables 5 through 8.

Table 1. Trichloroethylene (TCE) Removed from a Sealed Experimental Chamber by Houseplants During a 24-h Exposure Period

	Total Plant Leaf Surface Area (cm^2)	Total Micrograms Removed per Plant
Gerbera daisy *(Gerbera jamesonii)*	4,581	38,938
English ivy *(Hedera helix)*	981	7,161
Marginata *(Dracaena marginata)*	7,581	27,292
Peace lily *(Spathiphyllum "Mauna Loa")*	7,960	27,064
Mother-in-law's tongue *(Sansevieria laurentii)*	3,474	9,727
Warneckei *(Dracaena deremensis "Warneckei")*	7,242	13,760
Bamboo palm *(Chamaedorea seifritzii)*	10,325	16,520
Mass cane *(Dracaena massangeana)*	7,215	10,101
Janet Craig *(Dracaena deremensis "Janet Craig")*	15,275	18,330

Table 2. Benzene Removed from a Sealed Experimental Chamber by Houseplants During a 24-h Exposure Period

	Total Plant Leaf Surface Area (cm^2)	Total Micrograms Removed per Plant
Gerbera daisy *(Gerbera jamesonii)*	4,581	107,653
Pot mum *(Chrysanthemum morifolium)*	4,227	76,931
English ivy *(Hedera helix)*	1,336	13,894
Mother-in-law's tongue *(Sansevieria laurentii)*	2,871	28,710
Warneckei *(Dracaena deremensis "Warneckei")*	7,242	39,107
Peace lily *(Spathiphyllum "Mauna Loa")*	7,960	41,392
Chinese evergreen *(Aglaonema "Silver Queen")*	3,085	14,500
Marginata *(Dracaena marginata)*	7,581	30,324
Bamboo palm *(Chamaedorea seifritzii)*	10,325	34,073
Janet Craig *(Dracaena deremensis "Janet Craig")*	15,275	25,968

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Table 3. Formaldehyde Removed from a Sealed Experimental Chamber by Houseplants and Soil During a 24-h Exposure Period

	Total Plant Leaf Surface Area (cm^2)	Total Micrograms Removed per Plant
Banana *(Musa oriana)*	1,000	11,700
Mother-in-law's tongue *(Sansevieria laurentii)*	2,871	31,294
English ivy *(Hedera helix)*	985	9,653
Bamboo palm *(Chamaedorea seifrizii)*	14,205	76,707
Heart leaf philodendron *(Philodendron oxycardium)*	1,696	8,480
Elephant ear philodendron *(Philodendron domesticum)*	2,323	9,989
Green spider plant *(Chlorophytum elatum)*	2,471	10,378
Golden pothos *(Scindapsus aureus)*	2,723	8,986
Janet Craig *(Dracaena deremensis "Janet Craig")*	15,275	48,880
Marginata *(Dracaena marginata)*	7,581	20,469
Peace lily *(Spathiphyllum "Mauna Loa")*	8,509	16,167
Lacy tree philodendron *(Philodendron selloum)*	2,373	8,656
Chinese evergreen *(Aglonema modestum)*	1,894	4,382
Aloe vera	713	1,555

Table 4. Chemicals Removed by Household Plants from a Sealed Experimental Chamber During a 24-h Exposure Period

	Formaldehyde			Benzene			Trichloroethylene		
	Initial (p/m)	Final (p/m)	Percent Removed	Initial (p/m)	Final (p/m)	Percent Removed	Initial (p/m)	Final (p/m)	Percent Removed
Mass cane	20	6	70	14	11	21.4	16	14	12.5
Pot mum	18	7	61	58	27	53	17	10	41.2
Gerber daisy	16	8	50	65	21	67.7	20	13	35
Warneckei	8	4	50	27	13	52	20	18	10
Ficus	19	10	47.4	20	14	30	19	17	10.5
Leak control	18	17.5	2.8	20	19	5	20	18	10

Note: Plants were maintained in a commercial-type greenhouse until ready for testing. Each test, 24-h in duration, was conducted in a sealed chamber with temperature and light intensity of 30 °C ±1 and 125 footcandles ±5, respectively.

Table 5. Benzene Removal from a Sealed Experimental Chamber by Houseplants During a 24-h Exposure Period

	Initial (p/m)	Final (p/m)	Percent Removed
English ivy	0.235	0.024	89.8
Janet Craig	0.432	0.097	77.6
Golden pothos	0.127	0.034	73.2
Peace lily	0.166	0.034	79.5
Chinese evergreen	0.204	0.107	47.6
Marginata	0.176	0.037	79.0
Mother-in-law's tongue	0.156	0.074	52.6
Warneckei	0.182	0.055	70.0
Leak test control	0.171	0.162	5.3
Soil control	0.119	0.095	20.1

Table 6. Trichloroethylene (TCE) Removal from a Sealed Experimental Chamber by Houseplants During a 24-h Exposure Period

	Initial (p/m)	Final (p/m)	Percent Removed
English ivy	0.174	0.155	10.9
Janet Craig	0.321	0.265	17.5
Golden pothos	0.207	0.188	9.2
Peace lily	0.126	0.097	23.0
Warneckei	0.114	0.091	20.2
Marginata	0.136	0.118	13.2
Mother-in-law's tongue	0.269	0.233	13.4
Leak test control	0.121	0.120	<1.0
Soil control	0.141	0.128	9.2

During the first-year studies, the only controls used were chambers free of plants to test for loss of chemicals from chamber leakage and pots with fresh potting soil without plants. It was then assumed that after correcting for controls, the removal of chemicals from the sealed chambers could be attributed to the plant leaves. Because of the low photosynthetic and metabolic rates expected from these plants at light levels of 125 to 150 footcandles, the high chemical removal rates attributed to these low-light-requiring houseplants were puzzling.

In an effort to determine the exact mechanism(s) involved in chemical removal from the plant-soil system, plants were tested with foliage and then the same pots and soil were tested again after removing all foliage. Controls using full plant foliage with pea gravel covering the soil were also tested (Table 7). A microbiologist was brought into these studies to determine themicrobial profile found in the potting soils.

Early tests demonstrated that potting soil, after all foliage had been removed, was more effective in removing benzene than pots containing full foliage and soil. However, further studies and careful observation determined that this phenomenon occurred only when large amounts of foliage covered the potting soil surface, reducing contact between the soil and the air inside the chamber. Thus, some of the lower leaves were removed, allowing maximum contact between the soil-root zone and the chamber air containing toxic chemicals. Results of these new studies are shown in Tables 7 and 8.

Table 7. Benzene Removal from a Sealed Experimental Chamber by Houseplants in Potting Soil and the Same Potting Soil After Removing all Plant Foliage During 24-h Exposure Periods

	Initial (p/m)	Final (p/m)	Percent Removed
Marginata			
Full foliage	0.343	0.144	58.0
Foliage removed	0.348	0.175	49.7
Fresh potting soil control	0.206	0.164	20.4
Leak test, empty chamber control	0.215	0.199	7.4
Marginata			
Full foliage	0.176	0.037	79.0
Full foliage and soil covered with pea gravel	0.205	0.069	66.3
Janet Craig			
Full foliage	0.369	0.077	79.1
Foliage removed	0.321	0.176	45.2
Golden pothos			
Full foliage	0.122	0.040	67.2
Foliage removed	0.175	0.062	64.6
Fresh potting soil control	0.099	0.091	8.1
Leak test, empty chamber control	0.262	0.254	3.1

Table 8. Benzene Removal and Soil Bacterial Counts of a Chinese Evergreen Plant After Being Exposed for Several 24-h Periods to Benzene in a Sealed Experimental Chamber

	Percent Removed	Soil Bacterial Counts (cfu/g)
Initial exposure	47.6	3.1×10^4
After six weeks of intermittent exposure	85.8	5.1×10^4

Although the bacterial counts correlated with increased chemical removal in some of the studies as shown in Table 8, this finding was not consistent. Therefore, other yet unidentified biological factors may also be important. Data from this two-year study indicate that when the same plants and potting soil are constantly exposed to air containing such toxic chemicals as benzene, their capacity to continuously clean the air improves as shown in Table 8. This is not surprising, since it is a well-established fact that microorganisms have the ability to genetically adapt, thereby increasing their ability to utilize toxic chemicals as a food source when continuously exposed to such chemicals. This phenomenon is currently used to remove toxic chemicals from wastewater.[31-37]

Bacterial isolates found in the soil in which mother-in-law's tongue had been growing for a long period were *Alcaligenes, Bacillus, Curtobacterium, Flavobacterium, Micrococcus, Myxococcus,* and *Pseudomonas. Arthrobacter, Bacillus,* and *Leuconostoc* were found in marginata root soil. Bacteria such as *Bacillus, Flavobacterium, Leuconostoc,* and *Micrococcus* were also found in the Chinese evergreen potting soil. The peace lily potting soil contained *Aureobacterium, Bacillus, Curtobacterium, Micrococcus, Pseudomonas,* and *Streptomyces.* These are common soil microorganisms and most are known to be capable of biodegrading toxic chemicals when activated by plant root growth.

Results of the activated carbon-houseplant studies are shown in Figures 3 and 4. Although this research effort was not part of the NASA-ALCA two-year study, it is an essential component in the development of an indoor air pollution control system with plants to remove high concentrations of pollutants such as cigarette smoke and organic solvents. This biological system also utilizes plant roots and their associated microorganisms to purify indoor air; it differs from the potted plant study reported here in that a fan is used to rapidly move large volumes of air through an activated carbon filter. This filter adsorbs air pollutants and holds them until the plant roots and microorganisms can utilize them as a food source; therefore, bioregenerating the carbon.

To assure that no disease-causing microorganisms were released into the room from the carbon-plant filter, exhaust air from the filters was analyzed for microorganisms. To date, no pathogenic microorganisms have been found in the filter exhaust air.

It is common knowledge that plants give off trace levels of volatile organic chemicals under certain conditions, so metabolic off-gassing studies were conducted by screening several of the ALCA plants. These low-light-requiring plants were normally maintained at relatively low metabolic rates; therefore, one would not expect significant off-gassing of ethylene, terpenes, or any other metabolite. Gas chromatograph-mass selective detector studies using Tenax adsorption tubes to analyze the air inside the sealed experimental chamber indicated that the levels of plant metabolites were negligible.

As temperature and light levels are increased, it is expected that indoor pollution removal rates will increase along with some plant metabolite off-gassing. Increased oxygen production and carbon dioxide removal should also increase the rate of leaf participation in the removal rates of trace volatile organic chemicals.

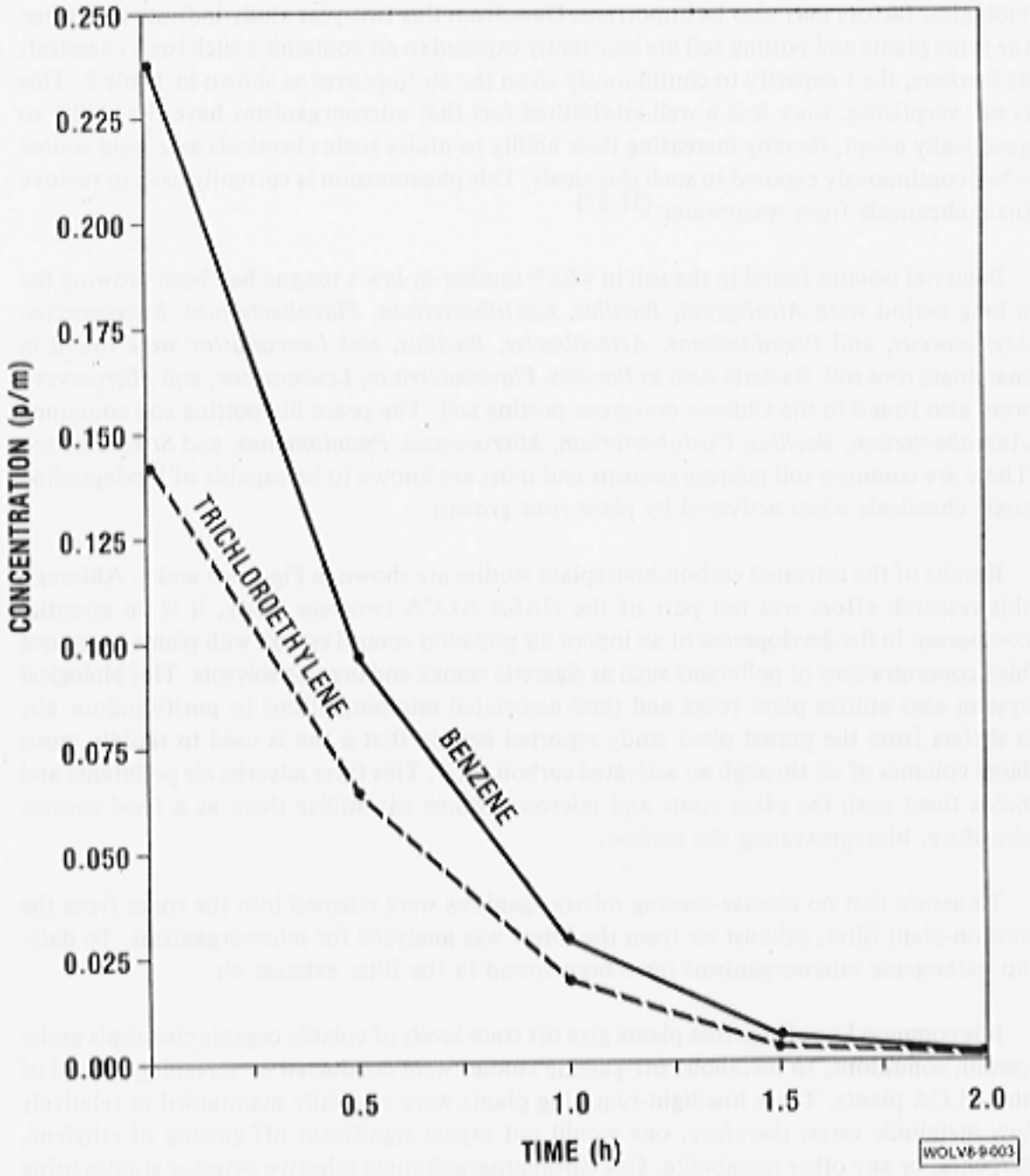

Figure 3. Removal of low concentrations of benzene and trichloroethylene from the air inside sealed experimental chambers using golden pothos in an 8-in. activated carbon filter system.

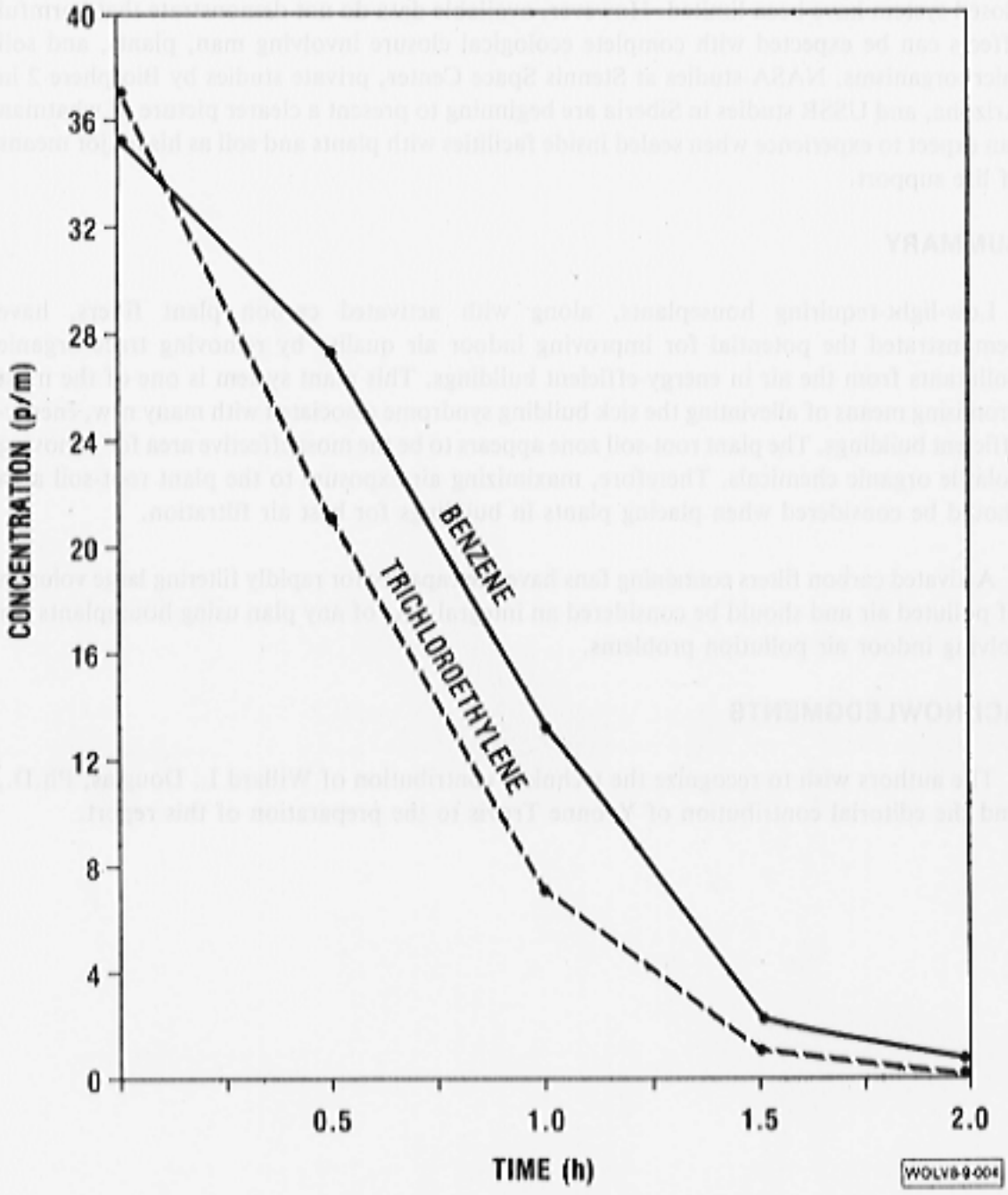

Figure 4. Removal of high concentrations of benzene and trichloroethylene from the air inside sealed experimental chambers using golden pothos in an 8-in. activated carbon filter system.

Studies of the beneficial or detrimental effects on man of volatile plant metabolites in a closed system have been limited. However, available data do not demonstrate that harmful effects can be expected with complete ecological closure involving man, plants, and soil microorganisms. NASA studies at Stennis Space Center, private studies by Biosphere 2 in Arizona, and USSR studies in Siberia are beginning to present a clearer picture of whatman can expect to experience when sealed inside facilities with plants and soil as his major means of life support.

SUMMARY

Low-light-requiring houseplants, along with activated carbon plant filters, have demonstrated the potential for improving indoor air quality by removing trace organic pollutants from the air in energy-efficient buildings. This plant system is one of the most promising means of alleviating the sick building syndrome associated with many new, energy-efficient buildings. The plant root-soil zone appears to be the most effective area for removing volatile organic chemicals. Therefore, maximizing air exposure to the plant root-soil area should be considered when placing plants in buildings for best air filtration.

Activated carbon filters containing fans have the capacity for rapidly filtering large volumes of polluted air and should be considered an integral part of any plan using houseplants for solving indoor air pollution problems.

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