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FOLIAGE PLANTS FOR REMOVING FORMALDEHYDE FROM CONTAMINATED AIR INSIDE ENERGY-EFFICIENT HOMES AND FUTURE SPACE STATIONS

BY:

B. C. WOLVERTON, PH.D.

AND

REBECCA C. McDONALD

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16. ABSTRACT

A sealed, plexiglas chamber with temperature and humidity control and illuminated externally with wide spectrum grow lights was used to evaluate the ability of golden pothos (*Scindapsus aureus*), nephthytis (*Syngonium podophyllum*), and sweet potato (*Ipomoea batatas*) to remove formaldehyde from contaminated air at initial concentrations of 16-19 ppm. Under the conditions of this study, the two low light-requiring plants, golden pothos and nephthytis, proved more efficient by removing 3874 and 3849 ug formaldehyde in the first 7h of exposure, respectively. The sweet potato removed approximately 50% less. The immediate application of this new technology should be in energy-efficient homes which have a high risk of this organic concentrating in the air due to outgassing of urea-formaldehyde foam insulation, particleboard, fabrics and various other synthetic materials. In addition, this technology is applicable to air purification and revitalization in future space stations which use biological means for developing a closed ecological life support system.

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INTRODUCTION

The accumulation of gaseous toxic substances in the air of poorly ventilated places has been known for many years, but only in recent years recognized as a potential indoor health hazard in energy-efficient homes (1-3). Aldehydes and other organic substances emanate from outgassing of urea-formaldehyde foam insulation, particleboard, plywood and fabrics. Other sources of formaldehyde include cigarettes and indoor cumbustion. Owing to the ubiquitous and increasing use of resins and solvents in the materials just mentioned, indoor formaldehyde concentrations have increased significantly over the past years. The adoption of energy-saving proposals to reduce ventilation rates in homes has aggravated problems of indoor air quality and increased potential health hazards. Similar problems occur with space travel and space stations.

In addition, man also becomes a source of air pollution in closed systems. Volatile substances are released in exhaled air, intestinal gases, perspiration, urine, and feces. It has been established that man gives off carbon monoxide, ammonia, hydrogen, hydrogen sulfide, methane, volatile fatty acids, phenol, indol, methylindole, mercaptans, aldehydes, nitrogen oxides and various hydrocarbons to the surrounding atmosphere.

Formaldehyde is presently one of the organic chemicals receiving the most attention as an indoor air pollutant because of its widespread use in products found in homes and house trailers. The high surface-to-volume ratio of particleboard and plywood used as building materials in mobile homes, as well as lower air-exchange rates, cause formaldehyde to concentrate in these facilities. Irritation of the eyes, throat, and lungs, respiratory disorders, and allergies have been associated with high formaldehyde concentrations (4-10). Surveys of mobile and conventional homes have found formaldehyde concentrations from 0.01 ppm to 10.6 ppm (2). In comparison, atmospheric concentrations usually average less than 0.1 ppm. At present, the Occupational Safety and Health Administration standard for formaldehyde is 3 ppm. The National Institute for Occupational Safety and Health has recommended that this industrial regulation be lowered to 1 ppm (2).

Prolonged exposure to formaldehyde also appears to decrease the threshold level for sensitivity. Studies in rats and mice done by the Chemical Industry Institute of Toxicology have found that formaldehyde induces nasopharyngeal carcinoma after several months of exposure at 15 and 16 ppm, 6 hours per day, 5 days per week. Dose-related histologic changes were observed in the nasal mucosa of rats exposed at 2 and 6 ppm for similar time periods. This demonstrates the potential danger of a complicated toxicological situation which can develop in energy-efficient homes during long-term habitation.

The accumulation of toxic substances in the atmosphere of future space stations, submarines or other sealed facilites can be prevented by incorporation of a special unit for absorption or inactivation of them in the life-support system. The basis of one approach for such a unit is biological. The potential of using biological means such as higher plants for removing air pollutants from closed systems has been demonstrated by the Russians. The Russians found that higher plants, such as wheat and vegetables, have the ability to remove toxic impurities from closed life-support systems (11).

Research applicable to the waste treatment processes needed in future closed ecological life-support systems has been pioneered in-house at the National Space Technology Laboratories for several years. NSTL's research focuses on the use of vascular aquatic plants and microbial filters for treating domestic waste and degrading toxic and hazardous chemicals in wastewaters to non-toxic, stabilized forms (12-25). In addition, we recognize the fact that higher plants have the ability to absorb air impurities through their leaves while absorbing water pollutants through their roots. Therefore, we should take full advantage of higher plants' ability to remove pollutants from both water and air at the same time (Figure 1). Recent support from the Director's Discretionary Funds has allowed the NSTL research to be expanded to include assessing the ability of foliage plants for air purification in energy-efficient homes and future space stations (Figure 2).

Golden pothos (*Scindapsus aureus*) and nephthytis (*Syngonium podophyllum*), low light-requiring houseplants, and sweet potato (*Ipomoea batatas*), a high light-requiring plant which produces vegetable and luscious vine, were the plants chosen for the initial studies. Golden pothos and nephthytis have low evapotranspiration rates, while sweet potato has a high one. Sweet potato is an especially good candidate because of its food production capability in future space stations.

EXPERIMENTAL METHODS AND MATERIALS

A clear, cubical chamber (shown in Figure 3) measuring 73.7 cm on each inside edge and constructed of 12.7 mm (0.5 in) thick plexiglas was used to contain the plants in a sealed environment. The top was removable and fitted with a rubber gasket and clamps to provide an airtight seal. Attached to the top was a copper coil, 10 m L x 12.7 mm OD, through which water maintained at 20° C was continously circulated in order to regulate the temperature and humidity inside the chamber. The temperature with the growth lights in place remained stable at 28.3° C (83° F). The artificial lights were General Electric wide spectrum growth lights which remained on continously. The average light intensity on the leaf surface of the plants through the plexiglas top was 3500 lux (325 F.C.). A battery-operated fan was placed in the chamber for continuous air circulation. A special porthole fitted with a septum was used to insert a Bendix disposable cartridge for monitoring formaldehyde in air with the aid of a Bendix calibrated hand pump designed for that purpose. The detectable concentration range of the Bendix cartridge is 2 to 20 ppm formaldehyde.

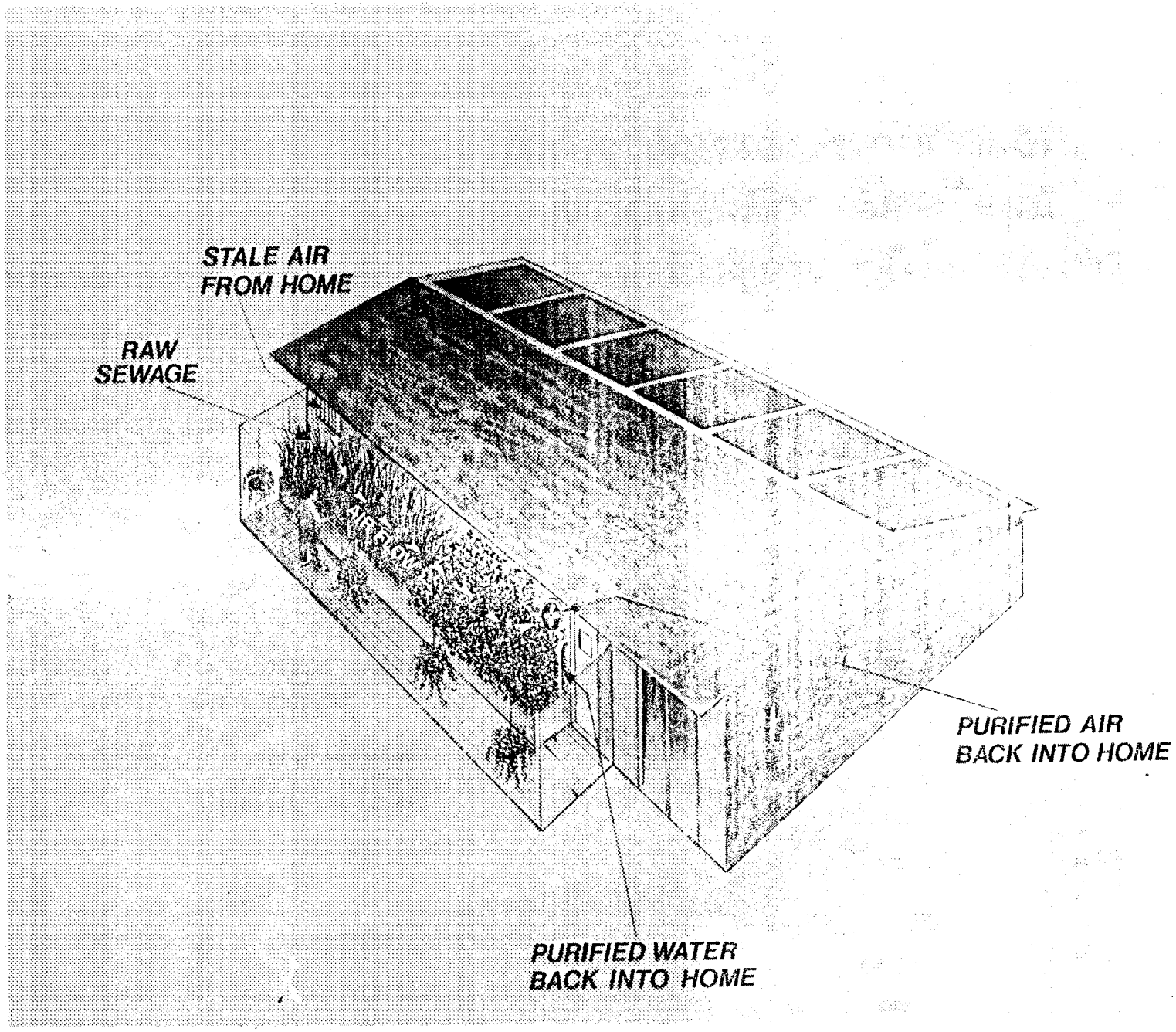

Figure 1. Artist's concept of a home using plants and microorganisms for sewage treatment and air purification.

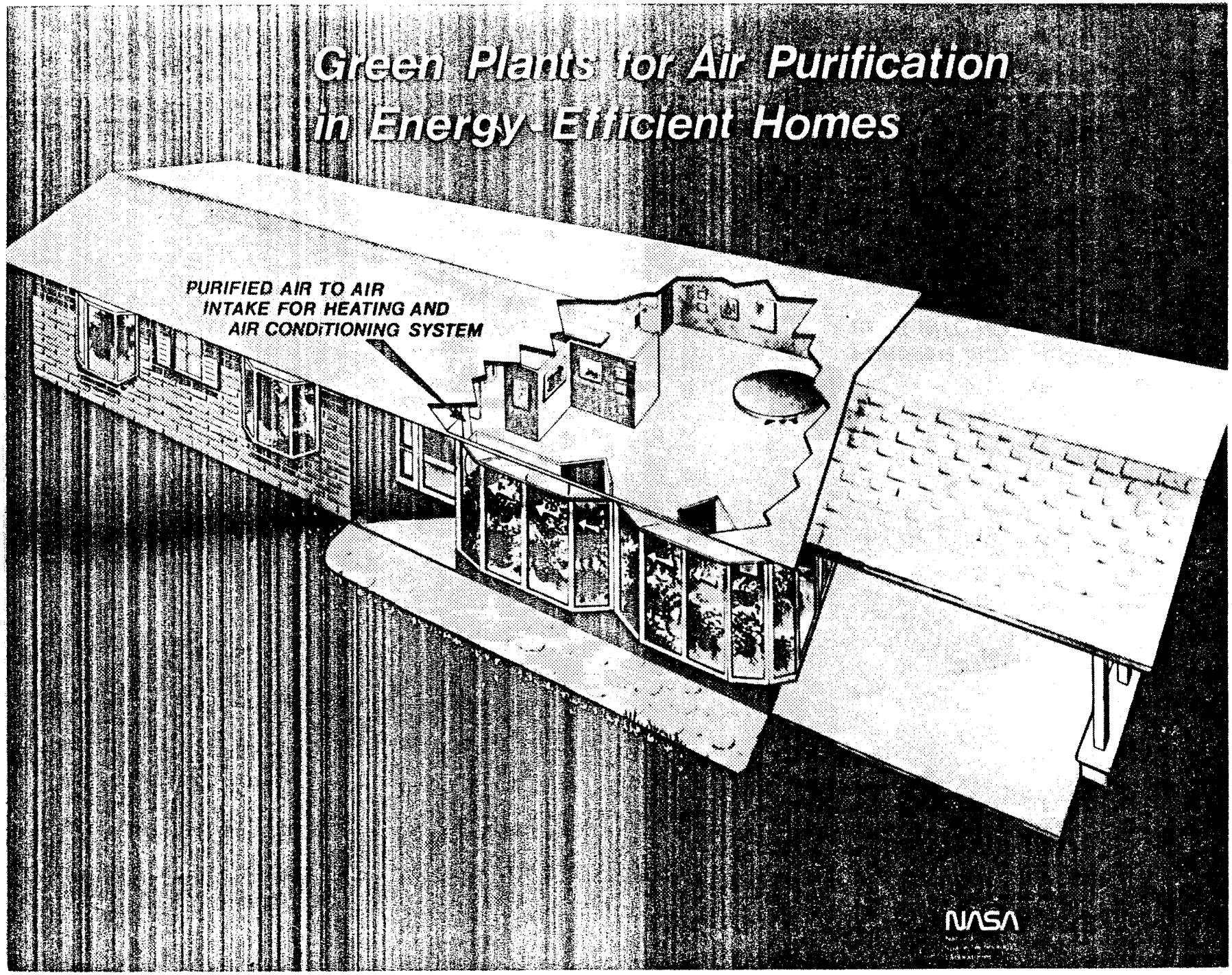

Figure 2. Biological unit for air purification in a sealed, energy-efficient home.

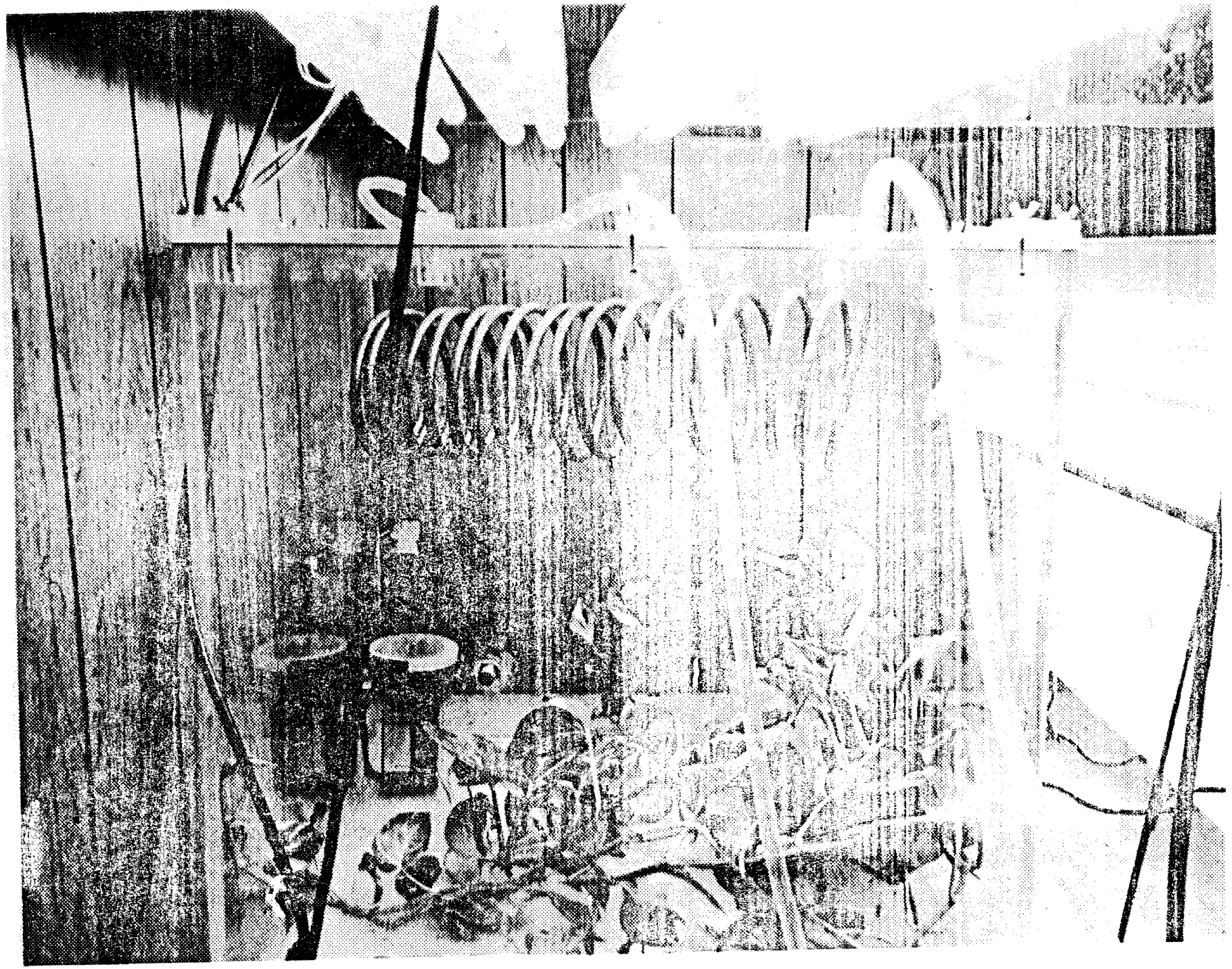

Figure 3. Plexiglas test chamber containing golden pothos (*Scindapsus aureus*).

The air in the chamber was contaminated with formaldehyde by pumping air into the chamber via a gas scrubbing apparatus half-filled with a 37% formaldehyde solution. Air was pumped through the solution and into the chamber at a rate of 250 ml/min for 120 sec.

After contamination, the chamber was allowed to equilibrate for five minutes, and the initial formaldehyde concentration was measured. The formaldehyde concentration was periodically analyzed in the same manner from that point on.

The chamber temperature from a thermometer placed inside the chamber and the barometric pressure was recorded at the time of each formaldehyde measurement. It was assumed that the pressure inside the chamber was equal to the atmospheric pressure.

The plants used in these experiments were acclimated for several weeks to approximately the same environmental conditions of lighting and temperature to minimize any stress resulting from the closed environment. The volume of each pot was estimated by measuring the volume of water which a similar pot could hold. The total leaf surface area of each plant used in these experiments was determined by tracing the shape of each leaf on paper of uniform consistency, cutting the tracings out and weighing them. The surface area was calculated from the total weight of the tracings and the average cm^2/g of the paper.

The volume of contaminated air in the chamber was computed as follows:

[volume of contaminated air, V_{ca}] =

[total chamber volume] - [Cu coil volume] - [fan volume] - [pot volume, Vp]

or

$$V_{ca} = 400\ell - 1.3\ell - 1.7\ell - Vp$$

$$V_{ca} = 397\ell - Vp$$

Control experiments were conducted prior to placing plants in the system. These experiments were conducted with all the equipment in place except plants. Controls with and without pots containing soil were conducted to determine the degree potting soil containing microorganisms acts as a sink in removing formaldehyde. The air was contaminated with formaldehyde and monitored initially, after seven hours and twenty-four hours. The system proved to be airtight by no loss of formaldehyde in the plant-free and pot-free formaldehyde control experiments.

RESULTS AND DISCUSSION

The first two sets of experiments were performed to verify system closure and determine the absorbance capacity of the potting soil. In each set, three replicate experiments were set up and monitored initially and after 7 and 24 h. The empty chamber proved to be effectively sealed by its ability to maintain a constant formaldehyde concentration of 17 ppm over a 24 h period as shown in Table 1. The second set of experiments demonstrated that the potting soil absorbed atmospheric formaldehyde by reducing the formaldehyde concentration from 15 to 10 ppm in 24 h. This behavior was not surprising since soil is known to act as a sink for removing carbon monoxide and other chemicals from the air. The potting soil is not a sterile media either. Therefore, the natural microbial population will in turn metabolize non-refractive organics such as formaldehyde and restore the soil's capacity to absorb organics.

Three more sets of experiments were conducted similar to those described above with golden pothos, nephthytis, and sweet potato. The mean data is shown in Table 1. The effective volume of contaminated air (V_{ca}) was calculated to account for all items which reduced the void volume in the chamber excluding that of the plant biomass. The golden pothos and nephthytis were very close in leaf surface area, 6440 and 6442 cm^2, respectively. The sweet potato was approximately 12% smaller. The mean data for each experiment is graphically compared in Figure 4. The performances of the golden pothos and nephthytis were very close. The sweet potato removed only about half of that of the other two plants.

The actual mass of formaldehyde removed from the air is shown in Table 2. The V_{ca} was corrected to STP (standard temperature, 0° C, and pressure, 760 mm) according to the gas laws relationship of:

$$\frac{V_1P_1}{T_1} = \frac{V_2P_2}{T_2}$$

where the temperature is converted to °K by the equation °K = °C + 273°. The corrected V_{ca}, the formaldehyde concentration, and the fact that 1 ul of formaldehyde has a mass of 1.339 ug at STP was used to determine the total formaldehyde mass in the chamber at each monitoring interval.

The total mass of formaldehyde removed by the golden pothos and nephthytis was almost equal. These two plants are very similar in their photosynthetic requirements and were matched almost perfectly in leaf surface area. Since these two species are low light-requiring plants, they should be more metabolically active under the 3500 lux provided than the high light-requiring sweet potato. The data substantiates this theory. The sweet potato system removed approximately 50% less formaldehyde than the other two species.

Table 1. Mean data of the five experimental studies.

Experiment	Formaldehyde Conc. (ppm) @			Vca, ℓ	Mean temp., °C	Mean barometric pressure, mm	Mean leaf surface area, cm^2
	0h	7h	24h				
Controls w/o pots	17	17	17	397	28.3	765	0
Controls w/pots	15	12	10	389.4	28.0	765	0
Golden pothos	19	9	5	389.4	28.3	766	6440
Nephthytis	17	7	3	387.6	28.9	766	6442
Sweet potato	16	9	9	393.2	27.6	766	5636

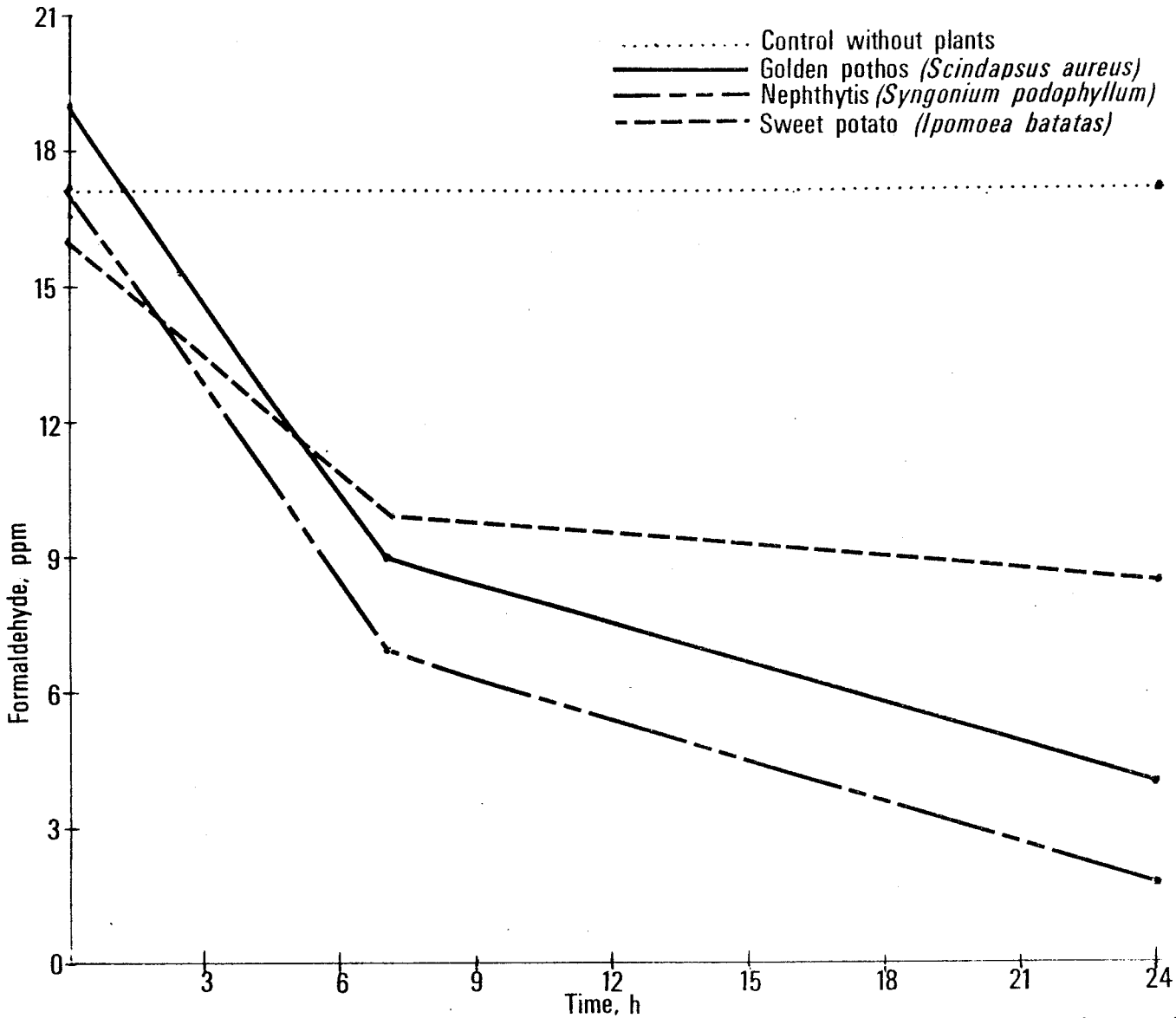

Figure 4. Formaldehyde concentration in air versus exposure time of experiments with golden pothos, nephthytis and sweet potatoes conducted in a closed chamber.

Table 2. Total formaldehyde (CH_2O) mass and the change (Δ = Initial - [7h or 24h]) in CH_2O as a function of time.

Experiment	Total Formaldehyde (ug) @			Δ Formaldehyde (ug) @	
	0h	7h	24h	7h	24h
Controls w/o pots	8238	8238	8238	0	0
Controls w/ pots	7136	5709	4757	1427	2379
Golden pothos	9042	4238	2379	4759	6663
Nephthytis	8038	3310	1418	4728	6620
Sweet potato	7706	4335	4335	3371	3371

The studies were restricted to 24 h intervals, because the sealed system was not equipped with means of removing oxygen or adding carbon dioxide. This restriction resulted in a decrease in the rate of formaldehyde removal due to depletion of the carbon dioxide and inhibitory effects of the increase of oxygen on the photosynthetic pathways of these plants.

The immediate application of this new technology should be in energy-efficient homes. As shown in Figure 2, homes can be built with bay window-type solariums where most plants can be grown. The amount of light entering rooms through windows increases after the winter equinox and decreases after the summer equinox. The angle of direct sunlight changes as the sun moves north in the spring and south in the fall. This condition can be taken advantage of by utilizing a southern exposure for growing high light-requiring plants year-round while creating a solar heat collecting system during the winter when direct sun rays penetrate the solarium. With the proper overhang, only indirect light will enter the solarium during the hot summer months, reducing heat buildup. Low light-requiring plants such as the golden pothos and nephthytis can also be grown year-round in a western, eastern or even northern exposure. Since foliage houseplants are an integral part of most homes, this simple, cost-effective means of purifying and revitalizing air in sealed energy-efficient homes should be readily accepted.

An extrapolation of the data to date in order to give one an idea of sizing a facility to purify the air in a home is as follows. At 25° C (77° F) and 760 mm pressure, either two large golden pothos or two large nephthytis potted in 3.8ℓ (1 gal) pots could remove 3874 or 3849 ug formaldehyde, respectively, every 24 h based on the 7 h data. This is equivalent to 0.1 ppm formaldehyde in a room 4.6m L x 3.7m W x 2.4m H (15' x 12' x 8'). Higher concentrations would require proportionally more plants. This is a very conservative estimate of these plants' capabilities with a short photoperiod of 7 h. As our studies progress, we will be able to better assess the true maximum capacity of these plants over a long period of time.

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APPROVAL

FOLIAGE PLANTS FOR REMOVING FORMALDEHYDE FROM CONTAMINATED AIR INSIDE ENERGY-EFFICIENT HOMES AND FUTURE SPACE STATIONS

by B. C. Wolverton, Ph.D. and Rebecca C. McDonald

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Energy Research and Development Administration programs has been made by the NSTL Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

A. M. Payne
Manager, Installation Operations