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Soil Bed Reactor Work of the Environmental Research Lab of the University of Arizona in Support of the Research and Development of Biosphere 2

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INTRODUCTION

The Environmental Research Laboratory of the University of Arizona was engaged through the Planetary Design Corporation, on behalf of Space Biospheres Ventures, developers of Biosphere 2, to assist with certain aspects of the scientific design of the Biosphere.

The areas of our contribution range from assistance with general engineering questions to extensive supporting work for the Intensive Agricultural Biome and a major program on issues having to do with air purification and the ultimate composition of the atmosphere within Biosphere 2. The scientific work reported in this paper was conducted under the direction of Dr. Robert Frye and he has prepared the paper that I have the pleasure of presenting.

Carl N. Hodges, Director
Environmental Research Laboratory

SOIL BED AIR PURIFIER RESEARCH AT ERL

Research at the Environmental Research Laboratory of the University of Arizona (ERL) in support of Biosphere 2 has been both of a basic and applied nature. One aspect of the applied research has involved the use of biological "reactors" for the scrubbing of trace atmospheric organic contaminants. These "reactors" so named by Dr. Heinrich Bohn, University of Arizona, who did original work in this field, may be used in both open and closed environments. Our research has involved a quantitative examination of the efficiency of operation of Soil Bed Reactors (SBR) and the optimal operating conditions for contaminant removal.

The basic configuration of a SBR (Figure 1) is that air is moved through a living soil that supports a population of plants. Upon exposure to the soil, contaminants are either passively adsorbed onto the surface of soil particles, chemically transformed in the soil to usable compounds that are taken up by the plants or microbes, or the compounds are directly used by the microbes as a metabolic energy source and converted to CO_2 and water.

The number and type of compounds degradable by soils is large. Figure 2 is a compilation of compounds that are either known to be degraded in soils or are suspected to be degradable from in vitro studies. We have worked with only a subset of these compounds in our experiments: methane, ethane, ethylene, propane, carbon monoxide and nitrous oxide.

Our SBRs come in many sizes and shapes, some of our research has been conducted with large SBRs having a diameter of approximately one meter. Those shown in Figure 3 in a greenhouse at ERL have been used primarily to study methane removal and the effect of operating a SBR on plant growth and development. Our results to

* Discussion paper, scientific and technical work prepared by Dr. Robert Frye, Research Scientist, Environmental Research Laboratory, University of Arizona. Paper presented by Carl N. Hodges. This is ERL contribution #90-19R.

date indicate that a SBR has no impact on plant productivity or phenology. That means that functioning soils can be used for both intensive cropping (biomass production) and air purification — a most important result for their utilization in space life support systems.

The factors that would impact the functioning of a SBR are those that impact soil microbe physiology. Factors such as soil moisture levels, temperature, organic matter content, soil type and air flow through the SBR should be important in determining the efficiency of its operation. Our research has focused primarily on organic matter content, soil type, and air flow rate as easily manipulated variables. In addition, we have found that the history of the SBR's exposure to contaminants is important.

In our large format SBRs we conducted a long term study on the removal of methane from an incoming air stream. This experiment was undertaken to examine whether the operation of a SBR declines with time. The graph in Figure 4 shows that with time a SBR becomes significantly more efficient at removal of methane. The three curves are fitted lines using the logistic population growth model. The implication of these results is that the efficiency of removal is dependent upon the population size of the microbial community in the soil and that upon exposure to a certain trace gas, that population increases over time. SBR #1 and #2 had different soil types which differed in organic matter content while SBR #3 had the same soil as in SBR #2 but only half the depth.

Another type of SBR we have used extensively at ERL is what we call our Aquaria SBRs (Figure 5). We have used these small systems to facilitate rapid acquisition of data which is not easily accomplished with the larger SBRs. These systems contain about 1.7 liters of soil in a container placed within a sealed 38 liter aquarium. The atmosphere within the aquarium is cycled through the soil with an aquarium pump. Flow rates of air through the

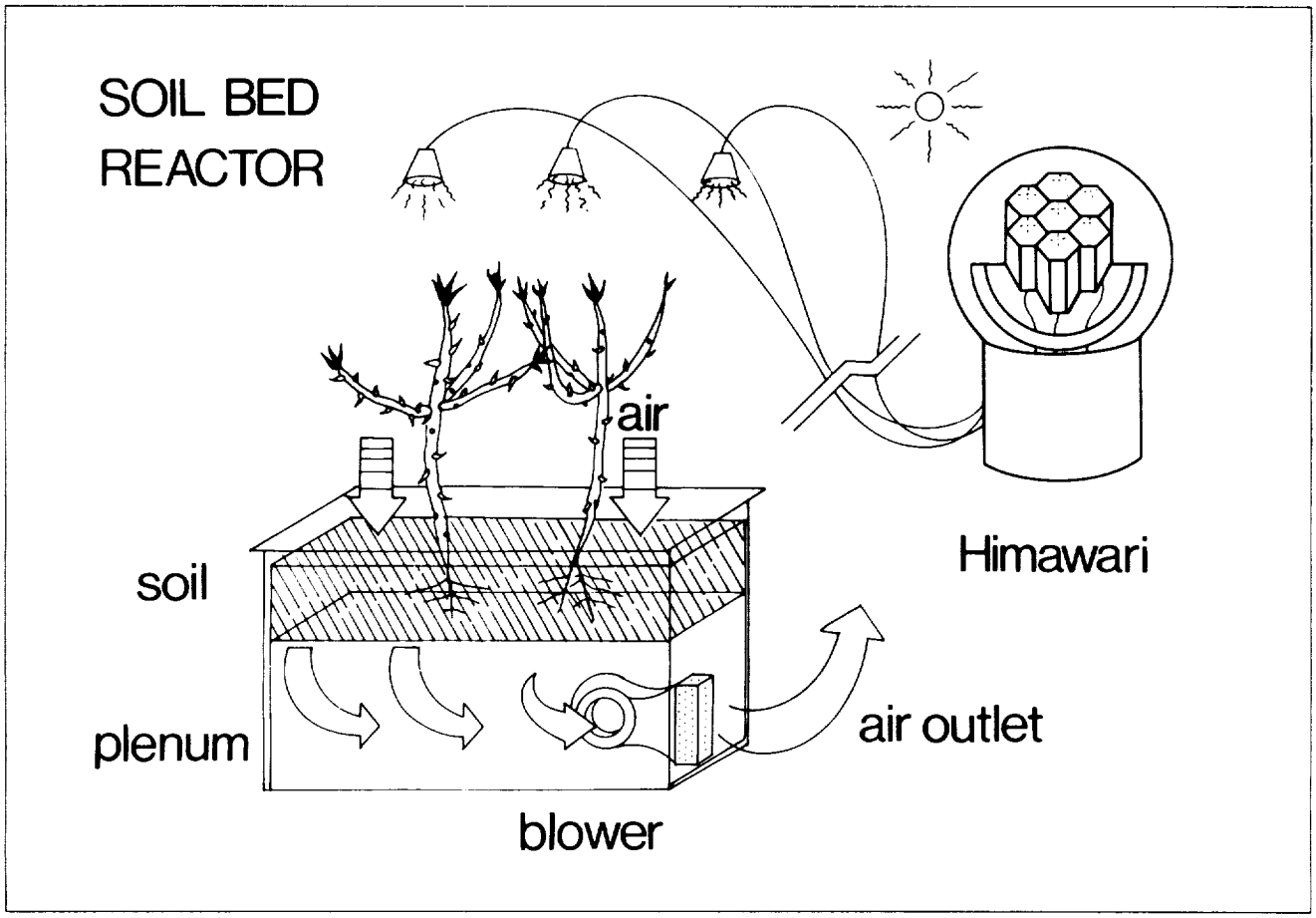

Figure 1. Schematic drawing of Soil Bed Reactor (SBR) for air purification.

Figure 2. Compounds known or suspected to be decomposed by soils or soil microorganisms.

Compound	Reference
Acetaldehyde	Fuller W.F. et al. 1983.
Acetic acid	Zavarzin, G.A. et al. 1977.
Acetoin	Bohn, H.L. 1977.
Acetylene	Smith, K.A. et al. 1973.
Acrolein	Fuller W.F. et al. 1983.
Alkyl benzene sulfonate	Horvath, R.S. et al. 1972.
Aldehydes	Fuller W.F. et al. 1983.
Ammonia	Hutton, W.E. et al. 1953.
Anthracene	Dalton, H. et al. 1982.
Benzene	Dalton, H. et al. 1982.
Benzoate	Dalton, H. et al. 1982.
Bicyclohexyl	Higgins, I.J. et al. 1979.
Bromomethane	Dalton, H. et al. 1982.
But-2-ene	Higgins, I.J. et al. 1979.
Butadiene (1,3-)	Van Ginkel, C.G. et al. 1987.
Butane	Hou, C.T. 1980.
Butene (1-)	Dalton, H. et al. 1982.
Butene (cis-2-)	Dalton, H. et al. 1982.
Butene (trans-2-)	Dalton, H. et al. 1982.
Butylbenzene (n-)	Horvath, R.S. 1972.
Butyl-cylohexane (n-)	Horvath, R.S. 1972.Table 1.
Butyric acid	Bohn, H.L. 1972.
Cadaverine	Bohn, H.L. 1977.
Caprolactone	Stirling, L.A. et al. 1977.
Carbon monoxide	Bartholomew, et al. 1982.
Chlorobenzoate (m-)	Dalton, H. et al. 1982.
Chlorofluoromethanes	Bohn, H.L. 1977.
Chloromethane	Dalton, H. et al. 1982.
Chlorophenol (m-)	Higgins, I.J. et al. 1979.
Chlorotoluene (m-)	Higgins, I.J. et al. 1979.
Cinerone	Horvath, R.S. 1972.
Cresol (m-)	Higgins, I.J. et al. 1979.
Cresol (o-)	Higgins, I.J. et al. 1979.
Cyanides	Bohn, H.L. 1977.
Cycloheptane	Beam, H.W. et al. 1974.
Cycloheptanone	Beam, H.W. et al. 1974.
Cyclohexanediol (1,2)	Beam, H.W. et al. 1974.
Cyclohexanediol (1,3)	Stirling, L.A. et al. 1977.
Cyclohexanediol (1,4)	Stirling, L.A. et al. 1977.
Cyclohexandione (1,2-)	Stirling, L.A. et al. 1977.
Cyclohexane	Stirling, L.A. et al. 1977.
Cyclohexanol	Beam, H.W. et al. 1974.
Cyclohexanone	Beam, H.W. et al. 1974.
Cyclohexene	Stirling, L.A. et al. 1977.
Cyclohexene oxide	Stirling, L.A. et al. 1977.
Cyclooctane	Beam, H.W. et al. 1974.
Cyclopentanone	Beam, H.W. et al. 1974.
Cymene (p-)	Dalton, H. et al. 1982.
Decane (n-)	Higgins, I.J. et al. 1979.
Dialkyl sulfides	Fuller W.F. et al. 1983.
Dichlorocatechol (3,5-)	Horvath, R.S. 1972.
Dichlorodiphenyl methane (p,p`-)	Horvath, R.S. 1972.
Diethyl ether	Dalton, H. et al. 1982.
Dimethyl disulfide	Oremland, R.S. et al. 1989.
Dimethyl ether	Dalton, H. et al. 1982.
Diphenyl-2,2,2-trichloroethane (1,1-)	Horvath, R.S. 1972.
Dodecane (n-)	Perry, J.J. 1979.
Dodecylcyclohexane	Beam, H.W. et al. 1974.
Ethane	Dalton, H. et al. 1982.
Ethanol	Zavarzin, G.A. et al. 1977.
Ethylbenzene	Dalton, H. et al. 1982.
Ethylcyclohexane	Stirling, L.A. et al. 1977.
Ethylene	DeBont, J.A.M. 1976.
Flouro-4-nitrobenzoate (2-)	Horvath, R.S. 1972.
Flourobenzoate (o-)	Horvath, R.S. 1972.
Flouride	Bohn, H.L. 1977.
Formaldehyde	Grundig, M.W. et al. 1987.
Formate	Hou, C.T. 1980.
Heptadecylcylcohexane	Beam, H.W. et al. 1974.
Hexadecane	Beam, H.W. et al. 1974.
Hydrogen sulfide	Smith, K.A. et al. 1973.
Hydrogen	Zavarzin, G.A. et al. 1977.
Isoprene	Van Ginkel, C.G. et al 1987.
Isopropyl benzene	Higgins, I.J. et al. 1979.
Isopropylcyclohexane	Stirling, L.A. et al. 1977.
Isopropyltoluene (p-)	Horvath, R.S. 1972.
Lactic acid	Bohn, H.L. 1972.
Limonene	Dalton, H. et al. 1982.
Methane	Anthony, C. 1982.
Methanol	Dalton, H. et al. 1982.
Methyl mercaptans	Fuller W.F. et al. 1983.
Methyl sulfide	Smith, K.A. et al. 1973.
Methylcatechol (3-)	Horvath, R.S. 1972.
Methylcyclohexane	Stirling, L.A. et al. 1977.
Methylnaphthalene (1-)	Higgins, I.J. et al. 1979.
Methylnapphthalene (2-)	Higgins, I.J. et al. 1979.
Napthalene	Dalton, H. et al. 1982.
Nitric oxide	Bohn, H.L. 1972.
Nitrous oxide	Goyke, N. et al. 1989.
Ozone	Turner, N.C. 1973.
Octadecane	Perry, J.J. 1979.
Organophosphorus	Bohn, H.L. 1977.
Pentachlorophenol	Lagas, P. 1988.
Pentanol (n-)	Higgins, I.J. et al 1979.
Phenol	Schmidt, S.K. et al. 1985.
Phenyldecane (1-)	Higgins, I.J. et al. 1979.
Phenylnonane (1-)	Higgins, I.J. et al. 1979.
Phosgene	Turner, N.C. 1973.
Propane	Bohn, H.L. et al. 1988.
Propene	Dalton, H. et al. 1982.
Propylbenzene (n-)	Horvath, R.S. 1972.
Propylene	Hou, C.T. 1980.
Putrescine	Bohn, H.L. 1977.
Pyridine	Dalton, H. et al. 1982.
Pyrrolidone	Horvath, R.S. 1972.
Skatole	Bohn, H.L. 1972.
Styrene	Higgins, I.J. et al.1979.
Sulfur dioxide	Smith, K.A. et al. 1973.
Terpenes	Rasmussen, R.A. 1972.
Tetrachloromethane	Galli, R. et al. 1989.
Tetradecane	Perry, J.J. 1979.
Toluene	Dalton, H. et al. 1982.
Toluidine (p-)	Higgins, I.J. et al .1979.
Tridecane (n-)	Perry, J.J. 1979.
Triethylamine	Fuller W.F. et al. 1983.
Trichlorobenzoate (2,3,6-)	Horvath, R.S. 1972.
Trichloroethane (1,1,1-)	Galli, R. et al. 1989.
Trichloromethane	Galli, R. et al. 1989.
Trichlorophenoxy - acetic acid (2,4,5-)	Horvath, R.S. 1972.
Xylene (m-)	Higgins, I.J. et al. 1979.
Xylene (o-)	Horvath, R.S. 1972.
Xylene (p-)	Horvath, R.S. 1972.

SBR were chosen to bracket those expected to be used in Biosphere 2. Trace contaminants were injected at the beginning of an experiment through the sampling port. Periodically the atmosphere within these systems was sampled and subjected to analysis with a gas chromatograph. To minimize pressure differentials room air was injected into the aquarium to compensate for atmosphere removed.

The most significant finding of our SBR research was the discovery that SBRs are highly variable in their behavior. This is not surprising when one considers the complexity of any natural soil microbial community. We believe, however, that much of the variability of the performance comes not from the soil microbes themselves but rather the environment of the soil and the physical status of the soil bed air purifier. Factors such as rapidly changing soil moisture levels and the methods that soil was placed within a SBR container can result in variable channeling behavior of air through the soil. With channeling, considerable variation in exposure of the soil microbes to the trace contaminants can occur.

Despite the variability we found in SBR behavior the most consistent statistically significant factor in SBR performance was prior exposure to atmospheric contaminants. As shown in a previous figure, the efficiency of removal of contaminants increases with the duration of exposure to a particular contaminant. In the aquaria SBR this was particularly true for ethylene. This graph (Figure 6) shows the increasing efficiency of removal of ethylene over four weeks of exposure. Beginning with a removal rate not different from zero during the first 4 days (the first week is negative due to ethylene production by the soil) the removal of ethylene became essentially total at the end of four weeks. A removal per cent in excess of 100% indicates that the soil bed has removed both the injected ethylene and the ethylene produced by the soil itself.

Figure 3. Soil bed reactors, part of a 72 replicate experimental setup, used in studies on plant growth and development at the Environmental Research Laboratory, University of Arizona.

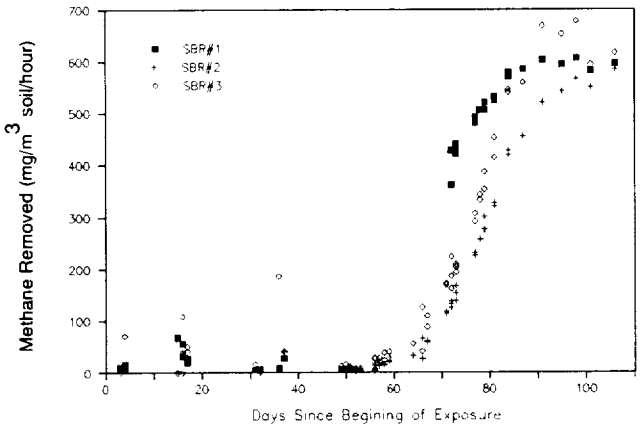

Figure 4. Methane removal in large SBRs as a function of soil type. The graphs also indicate the increased efficiency of removal over time.

The same pattern was noted for propane as displayed in Figure 7. Results for methane, carbon monoxide, and ethane showed similar patterns. Our hypothesis is simply that exposure to trace contaminants over time allows the growth of microbe populations in the soil that can utilize the contaminants. Anecdotally it appears that these populations can sustain periods of no exposure without significant declines in removal efficiency.

The graph in Figure 8 illustrates that the conditioning effect is observable in soils with inherently less organic matter and lower fertility. In this case unconditioned soil is soil within its first week of exposure to the contaminant gases whereas conditioned soil is the same soil after two weeks of exposure.

Any factor that might promote a larger, healthier population of soil microbes should also improve the scrubbing efficiency of a SBR. Figure 9 shows that when a soil is amended with organic matter (in the form of compost and peat moss) increased scrubbing efficiency should be expected. This graph is a comparison of exposure of the same

Figure 5. Aquaria SBR: 38 liter soil bed reactors used for benchtop tests of air pollutant control.

basic soil to contaminants when amended with organic matter and when left unamended. Clearly the amended soil is more efficient. This implies that soils that support a healthy population of plants would also be more efficient due to the plants' contribution to the soil organic matter within the rhizosphere. Current research should provide a more detailed investigation of this relationship soon.

The last factor I would like to discuss is that of air flow rate through a soil bed air purifier. Ethylene removal was studied as a function of flow rate in one of our early aquaria experiments. The results showed an optimal flow rate of somewhere between two and three atmospheric turnovers/day. This pattern was repeated with the other gases we examined and in our other experiments. While the trend was there this was not a statistically significant result due to the inherent variability of the data (Figure 10). Theoretically however this is not an unexpected pattern due to both enzymatic dynamics and increased channeling at higher flow rates.

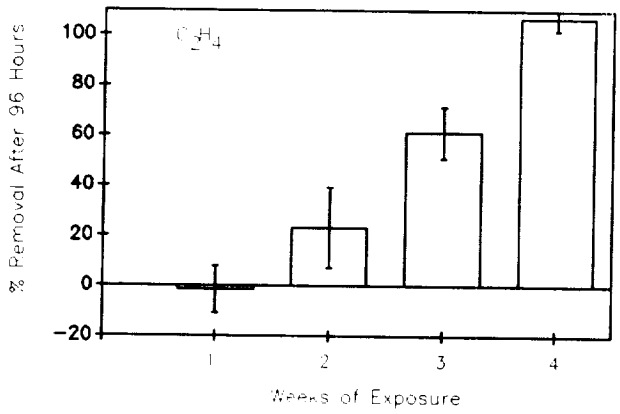

Figure 6. Conditioning effect of exposure to ethylene, a common atmospheric contaminant.

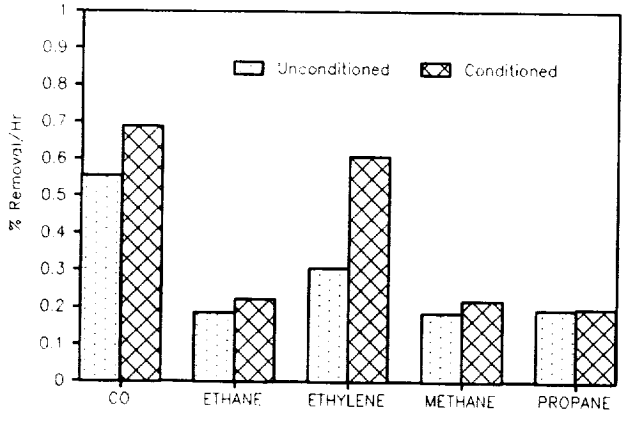

Figure 7. Gas removal in conditioned and unconditioned gray soil.

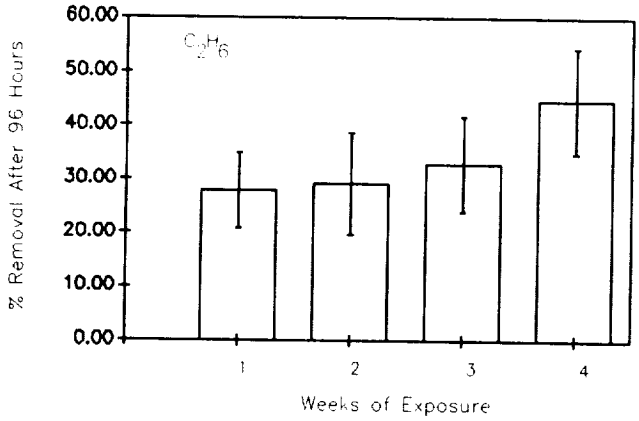

Figure 8. Conditioning effect of exposure to atmospheric contaminants.

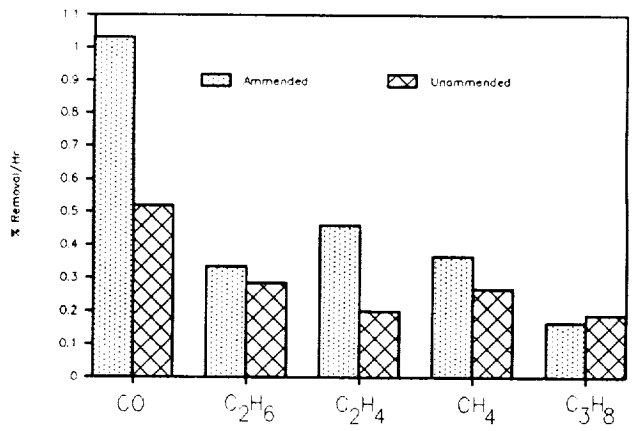

Figure 9. Effect of added organic matter on removal efficiency.

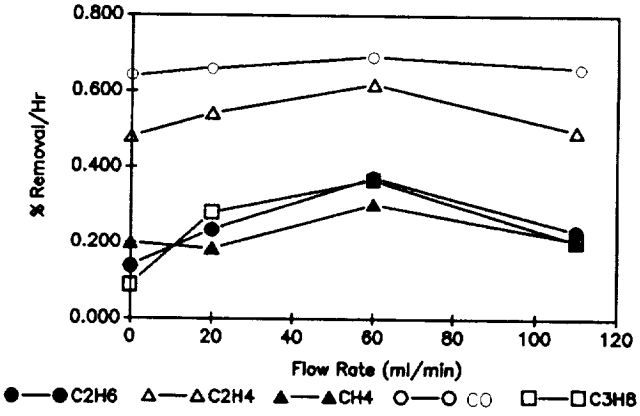

Figure 10. Removal of atmospheric contaminants by a SBR.

When averaged over several experiments the pattern is considerably reduced due to inter-experimental variability.

The last figures deal with the effectiveness of a SBR within a closed system such as Biosphere 2 or any closed system which could be established on another planetary body. During the summer of 1989 we set up a physical scale model of Biosphere 2. This model was to help verify mathematical models of trace contaminant behavior within Biosphere 2. The system consists of two aquaria, one scaled to represent the volume of the Intensive Agriculture Biome (IAB), Habitat, and Lung; and the other scaled to the size of the Wilderness Biomes and its Lung (Figure 11). The total volume of the system is 190 liters. The IAB aquarium has within it a SBR composed of a scaled volume of dirt and a pump to move the atmosphere within this aquarium through the soil. A second pump is located in the IAB to move air between the IAB aquarium and the Wilderness aquarium. The Wilderness aquarium contains a scaled quantity of soil and vegetation appropriate to the various biomes of Biosphere 2. We also placed a scaled Ocean within the Wilderness Biomes. During our first standardization runs we conducted we found evidence that supported our other research on the utility of SBR. In this experimental work, the removal of representative trace gases was examined when the SBR in the IAB aquarium was operating and when it was not. Figure 12 shows the results of this experiment. Note that for methane (CH_4), ethane (C_2H_6), propane (C_3H_8) and nitrous oxide (N_2O), operation of a SBR substantially reduces their concentrations within the system. Carbon monoxide (CO) seems relatively unaffected by operation of a SBR though this result could be due to the production of CO by the pump when it was operating.

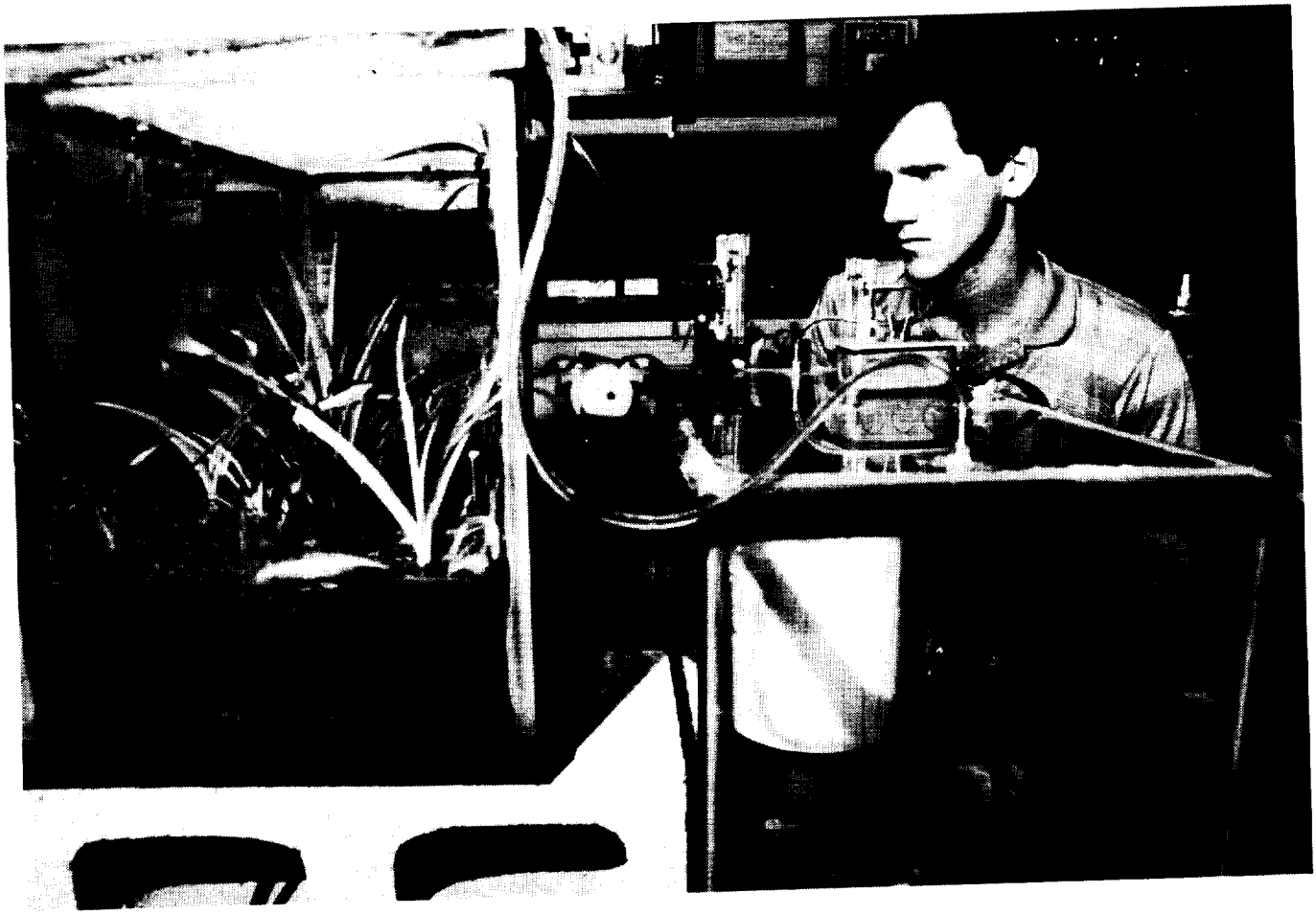

Figure 11. ERL researcher with physical scale model of Biosphere 2 used for soil bed reactor research.

Ethylene concentrations were higher when the SBR was operating than when it was not. This result is probably due to different production rates of ethylene during the two runs. Nevertheless, in both the case of ethylene and carbon monoxide, the atmospheric concentrations of these gases were reduced to less than 20% of their original levels. These data provide the first evidence that a SBR within a closed ecological system would be effective in limiting the levels of atmospheric contaminants.

An analysis of CO_2 production by SBRs revealed that no additional CO_2 is produced when the flow rate of air through a SBR is increased. The regression of the rate of CO_2 production on air flow rate was actually negative, that is, the higher the flow rate of air the lower the rate of CO_2 production. This phenomena is probably due to the effects of increased channeling, and the metabolic depression of the microbial communities due to cooling brought on by evaporation of soil moisture or limitation by soil moisture directly. The initiation of operation of a SBR does however lead to a dramatic increase in CO_2 levels in closed systems. This is due to forcing out the accumulated CO_2 within the soil pores. Continued operation however does not result in higher CO_2 production rates.

ERL, with the support of another group, the Planetary Design Corporation, has also investigated the use of small SBRs for use in office and home environments. This research has indicated that a SBR is also effective in minimizing airborne biological particulates. While the initial operation of a SBR will increase the amount of biological particulates, continued operation of the SBR will reduce the level of fungal spores to quantities less than that noted in a room without a SBR operating.

This research I have presented was conducted for Space Biospheres Ventures to assist in determining the optimal operation of the SBR to be located within Biosphere 2. While it was known in general that SBRs could remove trace atmospheric contaminants, the specific characteristics of SBR performance were unknown. We believe we have made considerable progress in elucidating some of the principles of SBR performance and operation and expect that both our own research and the

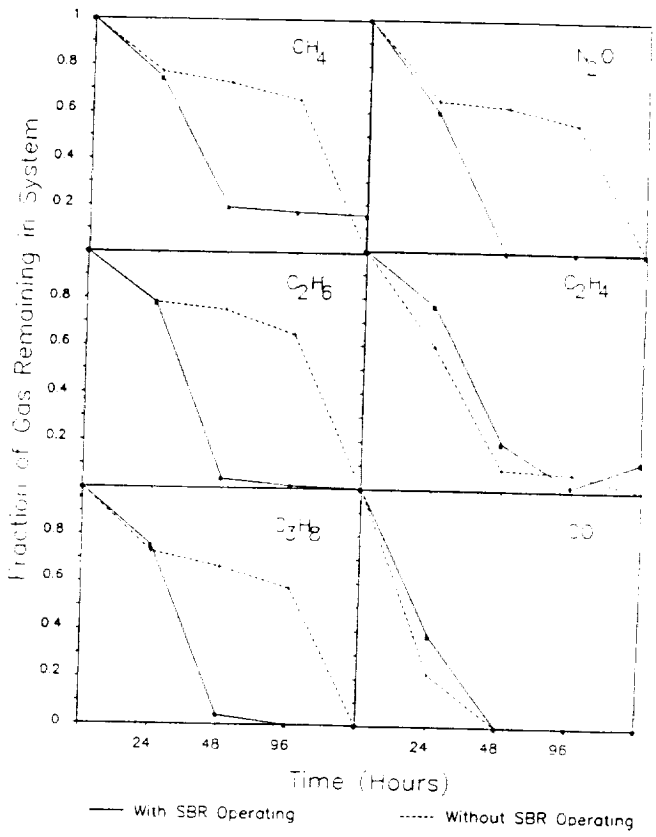

Figure 12. Atmospheric contaminant removal by a soil bed reactor in a closed ecological system.

research conducted by SBV in Biosphere 2 will answer many other questions. SBV has patent applications covering the advances made in SBR technology under this program which have tremendous commercial potential in reducing indoor and outdoor pollution while supporting productive crop or landscape plantings.

ERL is currently working with power generating companies in exploring the methodology of using SBRs and agriculture production for simultaneously reducing CO_2, CH_4, SO_2, and other emissions from power plants and increasing productivity to feed a hungry world. This is just one example of many important interactions between the results of work for Biosphere 1 and 2 benefiting the future success of both.