LIFE CYCLE BALANCING: AIR

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LIFE CYCLE BALANCING/AIR

O2/CO2 BALANCING AND VOC REMOVAL IN THE INDOOR ENVIRONMENT

BACKGROUND AND PURPOSE

Indoor air quality (IAQ) has become a significant determinant of occupant health and productivity as buildings have become more energy efficient. A growing body of evidence has indicated that air within buildings can contain more pollutants and contaminants than outdoor air. Moreover, most people spend a majority of their waking hours inside buildings. These two factors point to the need for both reducing indoor air pollutants at the source and removing them from the building interior once they have become airborne.

The Air Balance Model explores the potential of introducing plants, biofilters, and air purification technology into the indoor office environment to perform the following functions:

a) providing the oxygen (O_2) input requirements of the building occupants;
b) sequestering the carbon dioxide (CO_2) and water vapor output of the building occupants:
c) sequestering the CO_2 output of other sources in the building (if there is remaining capacity to do so);
d) removing pollutants and volatile organic compounds (VOCs) from indoor air; and
e) providing workplace privacy, acoustic control, and aesthetics.

The goal is to maintain indoor air at a higher quality level than outdoor air. Reducing the volume of outside air entering the building is part of the approach because providing fresh air solely by increasing outdoor air ventilation may increase the cost of operating the building's HVAC system and, in urban settings, simply exchange polluted outdoor air for contaminated indoor air.

The model being proposed is based on three related concepts: self-sustaining plant micro-ecosystems combined with biofilters and photocatalytic oxidation (PCO) air purification technology. The primary function of the plant micro-ecosystems is to balance the O_2 and CO_2 levels at the workstation scale and remove CO_2 from other sources within the building. Air purification at the scale of the workstation is performed primarily by biofilters containing microorganisms in a wetted porous rock substrate or a plant soil bed. The PCO system provides the majority of the air purification and detoxification functions at the scale of workstation and classroom clusters and entire floors.

The potential of plants in a micro-ecosystem to balance human O_2 and CO_2 requirements has been tested and evaluated in a closed environment at the Johnson Space Center in Houston under NASA's Early Human Testing Initiative (EHTI) Program in the design of regenerative life support systems for future space exploration. Certain plants can continuously provide the O2 production and CO2 removal functions for the physiological needs of humans. Experiments to date (1998) have "successfully demonstrated the use of higher plants for air revitalization for humans and the robustness of the plant systems as part of a human life support system [that] can be controlled to provide a specified desired performance" [Edeen and Barta 1996].

Although small scale experiments have concluded that plants can improve IAQ [Wolverton and Wolverton, 1992, 1993], the ability of plant biomass alone to purify and detoxify indoor air has been seriously challenged in field applications. Four major problems have been identified [Girman n.d., Levin 1992]. First, to scale up from small test chambers to building interiors would require an enormous amount of plant biomass to perform the same pollutant removal functions. For example, for the volume of a typical house, to achieve results similar to the test chamber results would require almost 700 plants. Second, most small scale experiments are performed using a static method in which a one-time injection of pollutant occurs. In building interiors, however, many sources emit pollutants continuously such as finishes and furnishings. Thus, while plants are removing pollutants, more of the same pollutants are being emitted at the same time. Third, with large amounts of plant biomass present in the interior environment of a building, humidity and microbial contaminants may become a serious concern to occupant comfort and health. Finally, plants themselves can be a source of VOCs. Chemicals for insect defense found on the surface of plant leaves are semi-volatile compounds. The general conclusion among IAQ researchers is that there is not sufficient data to support the theory that plants alone play a significant role in cleaning indoor air [Levin 1992].

Commercially available biofilter systems have been field tested in the semi-enclosed environment of a typical office building. A prototype biofilter composed of a porous mineral air scrubber, a hydroponic plant bed, and an aquatic plant aquarium (detailed description below) has demonstrated that removal of pollutants and VOCs (e.g., formaldehyde, toluene, and trichloroethylene) from recirculated indoor air can be accomplished in the workplace. The biofilter is designed to not only capture these materials but to also absorb or degrade them to less toxic substances. A wide variety of plant species – over 400 – can be utilized for biofiltration purposes. Field testing of the concept has yielded positive results [Chau 1997, Darlington and Dixon 1996].

PCO technology focuses light on a catalyst in the presence of water vapor to generate hydroxyl radicals that destroy airborne microbes. Hydroxyl radicals outperform chlorine and hydrogen peroxide in converting bio-aerosols to CO_2 (another source to be balanced) and water. Additionally, VOCs and other organic odors absorbed on the catalytic surface will be oxidized, the entire process known as photocatalytic oxidation.

The purpose of the Air Balance Model is to investigate whether an integrated clean air technology (ICAT) system which utilizes plant micro-ecosystems, biofilters, and PCO is appropriate for the NBSB project. If so, then further investigation into the design of a prototype may be warranted. The model is presented in three parts: 1) a narrative life cycle comparison of the typical outside air ventilation approach in buildings and the ICAT concept, 2) a detailed description of the Air Balance Systems Model, and 3) preliminary design and specification of a portable ICAT system prototype.

AIR QUALITY SCENARIOS: LIFE CYCLE DESCRIPTIONS

Typical Building Baseline

The source and transport phases of supplying fresh air for a typical building interior occurs when outside air enters the air handling system through an outside air intake louver located on an exterior wall. The process stage occurs when the outside air and building return air are mixed in an air mixing plenum upstream from the fan unit. Automatic dampers control the volume of both outside air and return air in the mixing plenum. The mixed air then passes through a combination of filters, heating coils, cooling coils, and humidifiers or dehumidifiers depending on outdoor climatic conditions and desired indoor comfort conditions. The distribution stage occurs when a fan unit circulates the conditioned air under pressure in ductwork to rooms and interior spaces (see Figure 1).

The source and transport stages of fresh air can also occur when outside air enters an interior space directly through operable doors and windows. Operable windows are rarely installed in modern non-residential buildings due to the lack of control over air volume, temperature, and humidity that enters the building. This option, however, is now being reconsidered. Research has indicated that both occupant health and productivity improve when an operable window is made available to users, even if they rarely open it.

The use stage occurs as the heating, ventilating and cooling (HVAC) system maintains the building's interior comfort level. In the conditioned space, supply air mixes with other gases in the building's interior environment. Human metabolism introduces a small amount of CO_2 into the indoor air. In addition, the outgasing of building materials and office machinery and products emit airborne pollutants and VOCs. This mixture is returned through ductwork back to the air handling equipment of the HVAC system. A portion of return air is exhausted, and the remainder re-enters the supply air flow along with new outside air. This process continues as long as the air handling system is operating (see Figure 2).

ICAT System Scenario

The proposed ICAT system utilizes the three components described above – plant micro-ecosystems, biofilters, and PCO units – to balance the O_2 and CO_2 requirements for human metabolism, absorb CO_2 from other sources, and remove airborne pollutants and VOCs. Each component is located at the point-of-use, in the case of the NBSB project, in the workstation and classroom spaces. The POC component can also be incorporated into centrally located air handling equipment. The point-of-use prototype ICAT equipment is designed to be portable, modular, and accessible for monitoring and maintenance. Additionally, each component is designed for workplace privacy, acoustic control, and furnishing aesthetics.

PLANT MICRO-ECOSYSTEM COMPONENT

Many factors influence the level of CO2 in the indoor environment including the number of people, their size, the physiological level of activity, the performance of the HVAC system, the presence of plants, the season of the year, and the time of day. The maximum concentration for an 8-hour period established by OSHA and other federal agencies is 5,000 parts per million (ppm). There have been cases documented where levels below 5,000 ppm have caused discomfort and headaches. Levels of 3,000 ppm have been measured in houses, schools, and offices.

Under typical conditions with outside air ventilation, indoor CO_2 levels are not physiologically important. However, if outside air intake rates are significantly lowered in energy-efficient buildings, then CO_2 accumulation may become a health concern for building users. A prototype ICAT system that can remove airborne pollutants, VOCs, and CO_2 solves this problem. Plants are therefore included in the micro-ecosystem component to remove indoor CO_2 and produce O_2.

One design objective is to make the plant micro-ecosystem component self-sustaining at the scale of the workstation, workstation/classroom cluster, or building floor by supplying all necessary soil nutrients and water from sources generated within these building scales. The planting bed soil can be periodically enriched by compost produced from organic waste recycling in vermiculture bins located at each workstation and workstation/classroom cluster. Water can be supplied at each building floor from the dehumidification condensate from the HVAC system.

A per person footprint for the plant micro-ecosystem component was established using NASA experimental data. The total plant stand area for O2 production and CO2 removal balance was demonstrated to be 120 square feet per person. This benchmark was established under controlled laboratory conditions and should therefore be regarded as a minimum.

Water vapor is a by-product of plant transpiration resulting from the need of the plants to maintain open leaf pores to sustain CO2 intake. The average amount of transpired water in the NASA experiments was about 1 pint per square foot of plant stand area per day (5 liters per square meter per day) although rates as high as 4 pints or 1/2 gallon per sq. ft. (20 liters per sq. m.) per day were documented. This volume of water will increase the humidity in the indoor environment and consequently influence the performance of the HVAC system, especially during the cooling mode.

BIOFILTRATION COMPONENT

The biofiltration process utilizes a complex and stable biological micro-community to improve air quality in an indoor environment. Filtration is accomplished by passing the indoor air stream through a combination of different media such as porous rock (e.g., zeolite or pumice), planting soil beds, plant canopies, water soaked surfaces, or aerated water. The biofilter is usually located in the workplace.

One prototype that has been field tested incorporates three components: 1) porous, vertical modules of constantly wetted, moss covered lava rock (scrubber), 2) a planter bed of hydroponically grown higher plants at the base and in front of the rock wall, and 3) an aquarium at the base of the plants containing a variety of aquatic and semi-aquatic plants. Aquarium water circulates through the hydroponic plantings, is pumped up to the top of the rock wall, and flows down the surface of the rock modules back into the aquarium (see Figure 3).

The air source is the interior air that circulates under fan pressure through a separate air handling system. The process stage occurs as the air flows through the biofilter. The air first passes through the plant canopy before entering the vertical modules of the wetted, moss-covered rock. A large plenum at the rear of the rock wall collects the air and circulates through return air ductwork to a particle filter and supply air fan. The air is then re-circulated into the space through supply air ductwork.

This prototype removed significant amounts of all VOCs monitored, but the rate varied considerably with each VOC tested. For example, water soluble and readily metabolized compounds such as formaldehyde, were most effectively removed. Other less soluble and more stable compounds such as trichloroethylene (TCE) were more difficult to remove.

Another type of biofilter medium combines activated carbon with wood-based/compost materials. The biofilter consists of a mixture of compost and wood chips which can be amended with either granular activated carbon (GAC) or perlite. Both the GAC and perlite mixture biofilters performed well, achieving very high rates of VOC removal, even for low water soluble compounds.

A per person or per square foot footprint of the biofiltration component has yet to be determined. The variables are the level and types of VOCs to be removed from the indoor air and the sort of biofilter medium to be utilized.

The release of water vapor as a by-product of plant transpiration and direct evaporation from the aquarium is also a factor to be considered in the sizing of the biofiltration component. Like the plant micro-ecosystem, this water vapor will increase the humidity in the indoor environment and consequently influence the performance of the HVAC system, especially during the cooling mode.

PHOTOCATALTYIC OXIDATION COMPONENT

During the photocatalytic oxidation (PCO) process, air pollutants are converted into benign compounds. The key step in the process is the exposure of a photocatalyst – a highly reactive chemical compound - to selective wavelengths of light. The light source can be either sunlight or electric light. The photocatalyst is applied as a thin coating on the inside of a reactor wall. As the air stream circulates through the reactor wall, the pollutants are chemically altered and cleansed air exits the system.

PCO has been demonstrated to be most effective on low-concentration and low-flow-rate waste streams. It normally operates at ambient temperatures and pressures. The available hardware is modular and portable and therefore suited to on-site air treatment for many indoor environment conditions and situations.

Two drawbacks to PCO systems are the lighting energy requirements and the by-products of the process – heat and carbon dioxide. The lighting energy required is about 1/2 watt per cubic foot per minute (cfm) of air delivery. For example, a 350 cfm unit uses about 170 watts of power. This will provide one complete air change per hour (ac/h) for a 2,000 sq. ft. space with a ceiling height of 10 feet or two ac/h for 1,000 sq. ft, of space. A typical floor area of the proposed NBSB project is roughly 24,000 sq. ft. Each typical floor would therefore utilize 24 PCO units for 2 ac/h requiring more than 4,000 watts of power. This is not a significantly large number, although with energy-efficient fixtures and compact fluorescent lamps, it may be enough power to illuminate 40 offices. This amount of electrical energy will also add heat to the indoor environment, adding to the cooling load performance of the HVAC system.

One of the by-products of the chemical conversion process is carbon dioxide. This will increase the level of CO_2 in the building and add additional balance load to the plant micro-ecosystem component of the ICAT system. The levels of CO_2 released by the PCO process have yet to be determined.

AIR BALANCE SYSTEMS MODEL

The Air Balance Systems Model examines the O_2 and CO_2 concentrations in a building, and attempts to achieve a balance between plant production and human consumption of O_2 and plant consumption and human production of CO_2 (see Figure 4). The assumptions regarding O_2 and CO_2 levels are:

• Oxygen inhaled per person per day:	1.85 lbs.
• Carbon dioxide exhaled per person per day:	2.2 lbs.
• Oxygen released per sq. ft. of plant stand area per day:	0.07 lbs.
• Carbon dioxide absorbed per sq. ft. of plant stand area per day:	0.1 lbs

For the NBSB project, the following schedule of building occupants was assumed:

- 8am - 5pm: 400
- 5pm - 10pm: 100
- 10pm - 8am: 20

Using the office, floor, and building dimensions as illustrated in the competition drawings, approximately 6,000 sq. ft. of plant stand area is required in the building. Since plants only photosynthesize when under light, a curve approximating different levels of light falling on the plants was derived. This is used more or less to simulate a fraction efficiency of the plants. For example, if there is 10% of the full light intensity, then the plants will produce 10% of their given oxygen production capacity. The lighting intensity curve is:

- 5am - 8am: 30%
- 8am - 4pm: 75%
- 4pm - 9pm: 40%
- 9pm - 5am: 10%

The calculations are very straightforward:

Oxygen added to building = O_2 released per sq. ft. plant * sq. ft. plants * light factor.
Carbon dioxide taken from building = CO_2 absorbed per sq. ft. plant * sq. ft. plants * light factor.
Oxygen taken from building = O_2 inhaled per person * num. of people in bldg.
Carbon dioxide added to building = CO_2 exhaled per person * num. of people in bldg.

The model is run over the span of one day, and shows the fluctuations of oxygen and carbon dioxide concentrations as people come in and out of work, and as light intensity grows and dims (see Figure 5). The final ratio of oxygen to carbon dioxide in the building is calculated as: (building O_2/CO_2)/(ambient O_2/CO_2), so the initial air has a ratio of 1.00.

Given the above assumptions, after one day, the ratio is 0.828, for a net decrease in oxygen, and increase in CO_2. The air quality reaches a balance when 10,000 sq. ft. of plants are introduced into the building, and reaches a final ratio of 0.991. This model currently does not have the plants decrease their efficiency with a lack of CO_2, due to a lack of data on this subject.

CONCLUSION: ICAT SYSTEM PROTOTYPE DESIGN

The questions of humidity control, energy consumption, and CO_2 releases must be addressed before final recommendations can be submitted regarding an integrated clean air treatment (ICAT) system for the NBSB project. However, a conceptual design has been created which illustrates one possible arrangement of prototype air treatment equipment at the workstation scale (see Figures 6 and 7) and the floor and building scale (see Figure 8).

At the workstation scale, each of the three ICAT components – plant micro-ecosystems, biofilters, and PCO units – are located in the occupied space and designed as portable office furnishings. The plant bed area per person is about 100-120 square feet and is coupled with vermiculture cabinets located below the plants. The biofilters are designed as vertical partitions for acoustic and visual privacy. Aquariums are included as water sources for hydroponically grown plants. The PCO units are small appliances, measuring about 12"x16"x30" in height., installed in the same type of movable frame as the other components.

At the floor and building scale, footprints for the plant micro-ecosystems and biofilters are indicated. These footprints correspond proportionately in area to the number of estimated building occupants. The PCO units can be sized according to the air purification needs of an entire building floor or zone and installed directly with the HVAC system. If air balance cannot be achieved at the scale of the building, then trees planted on site may assist in the balancing the O2/CO2 ratio.

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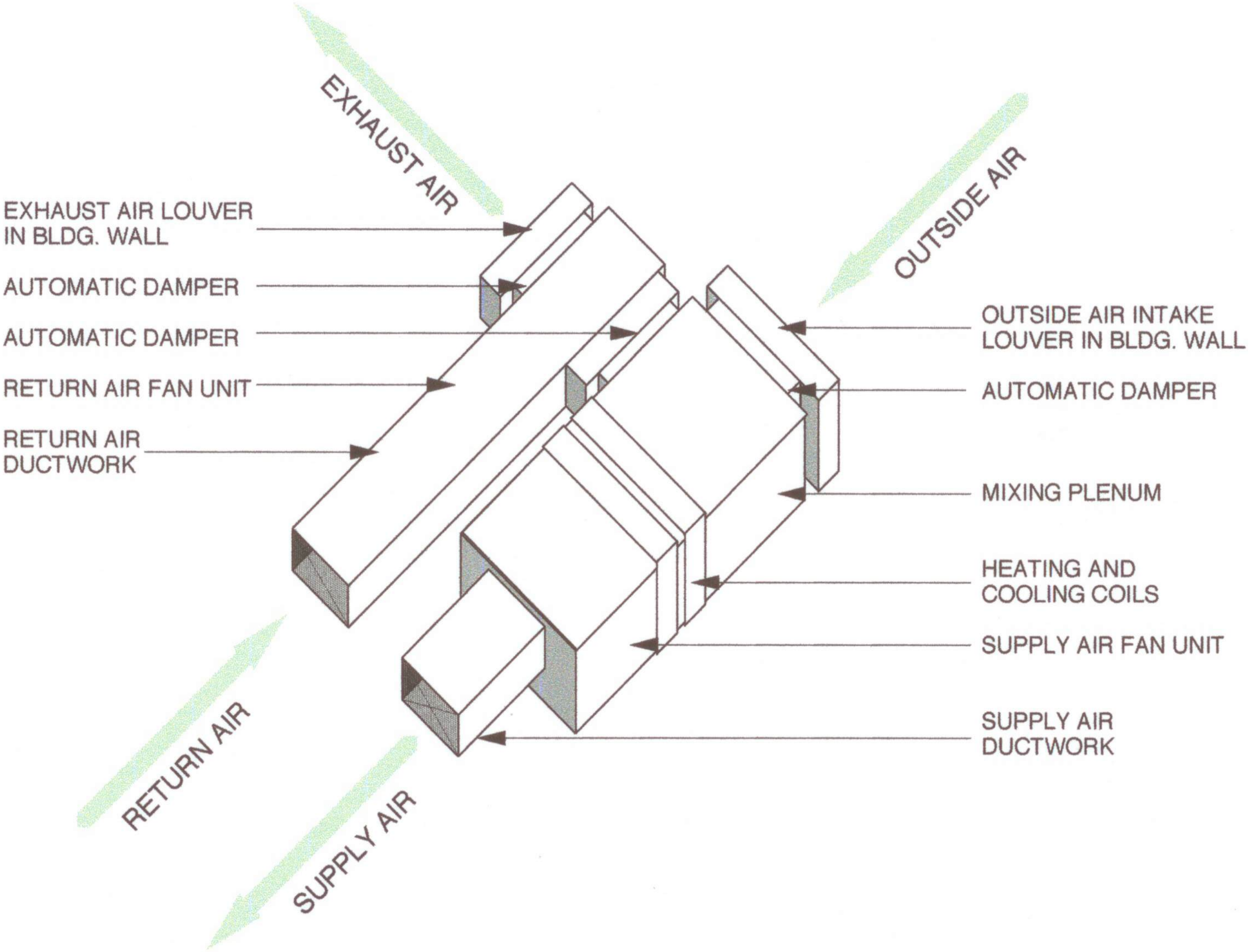
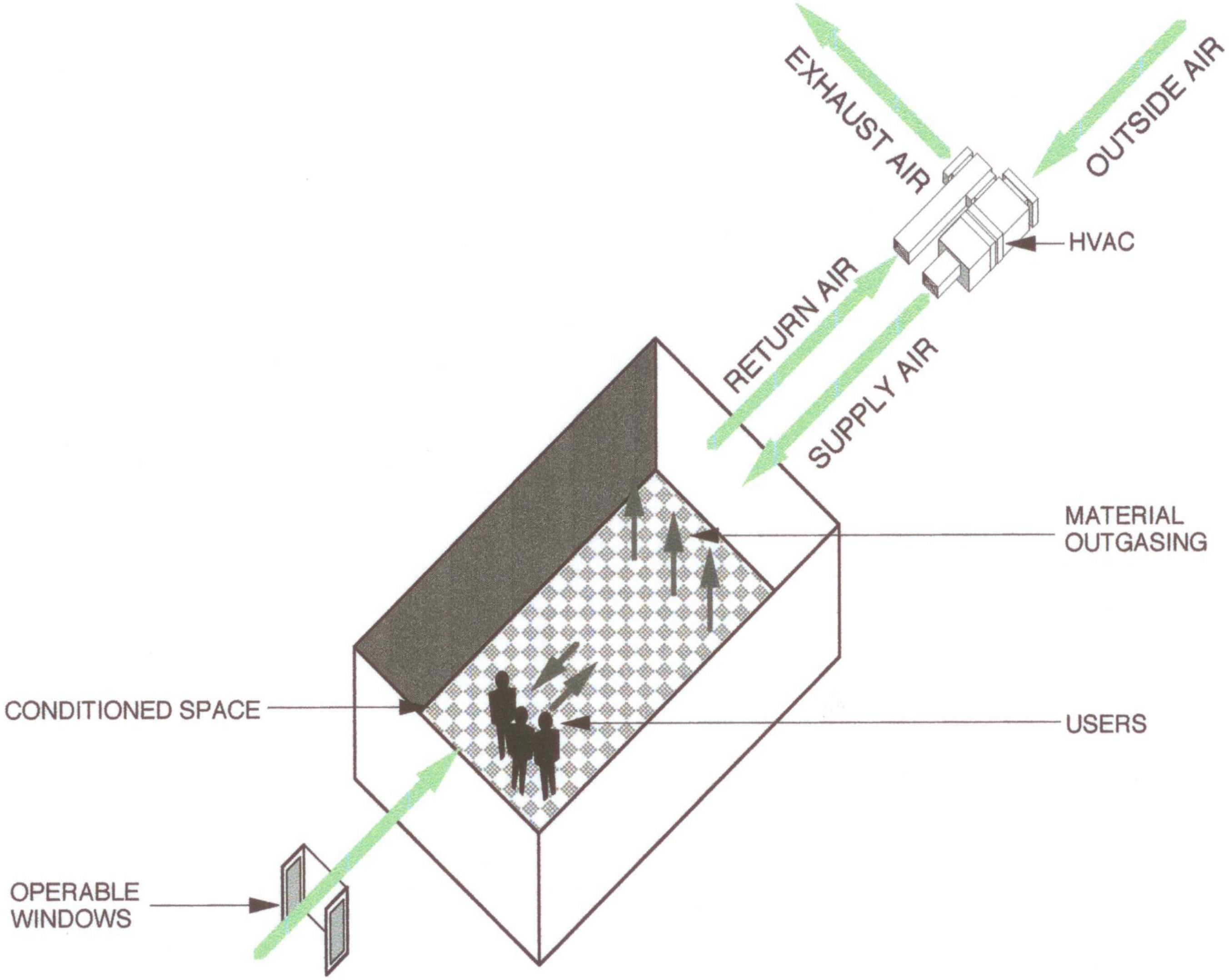
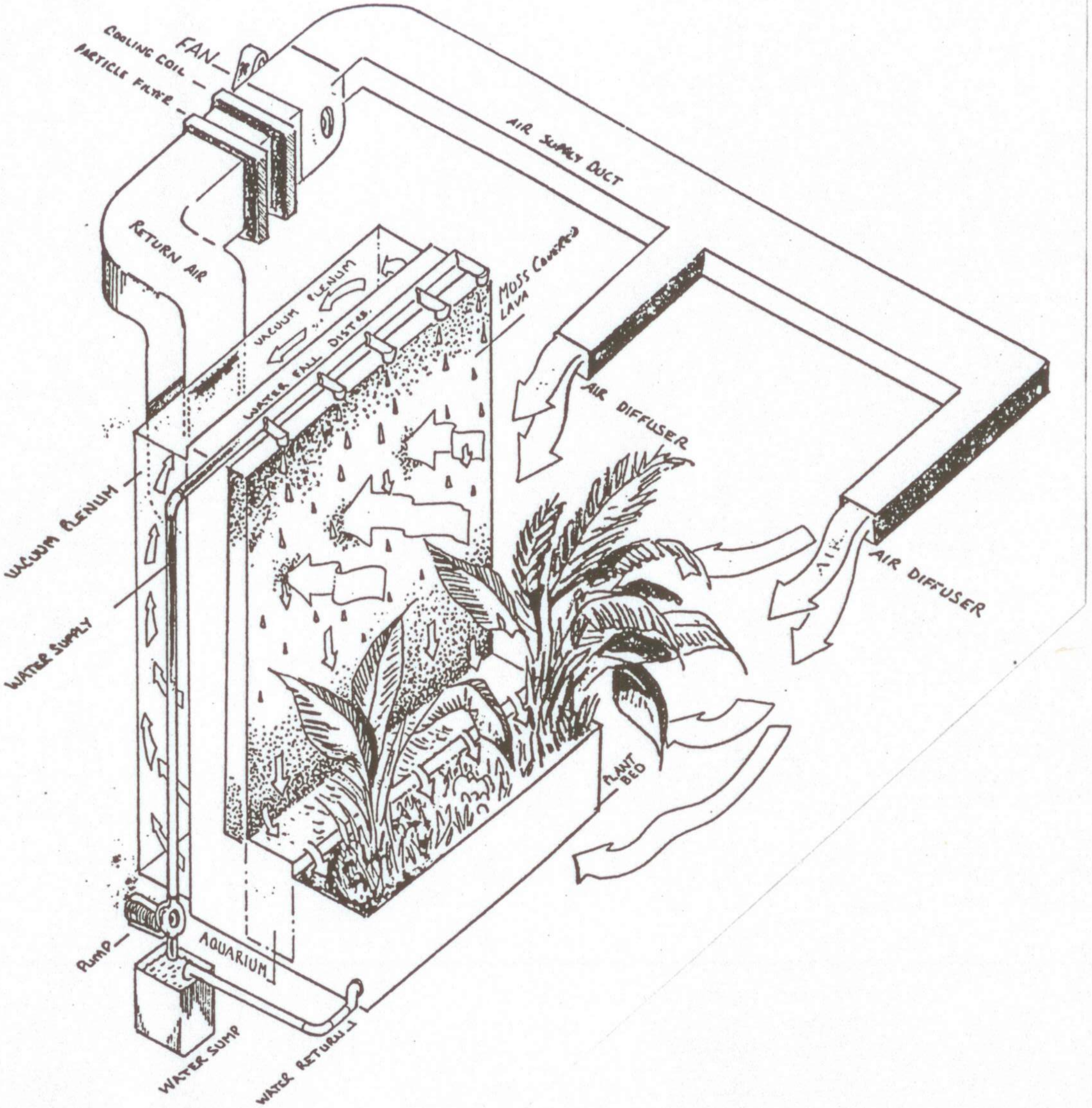


LIFE CYCLE BALANCING / AIR	**FIGURE 1** **GENERIC AIR HANDLING EQUIPMENT**	NO SCALE CMPBS 1998	🟩



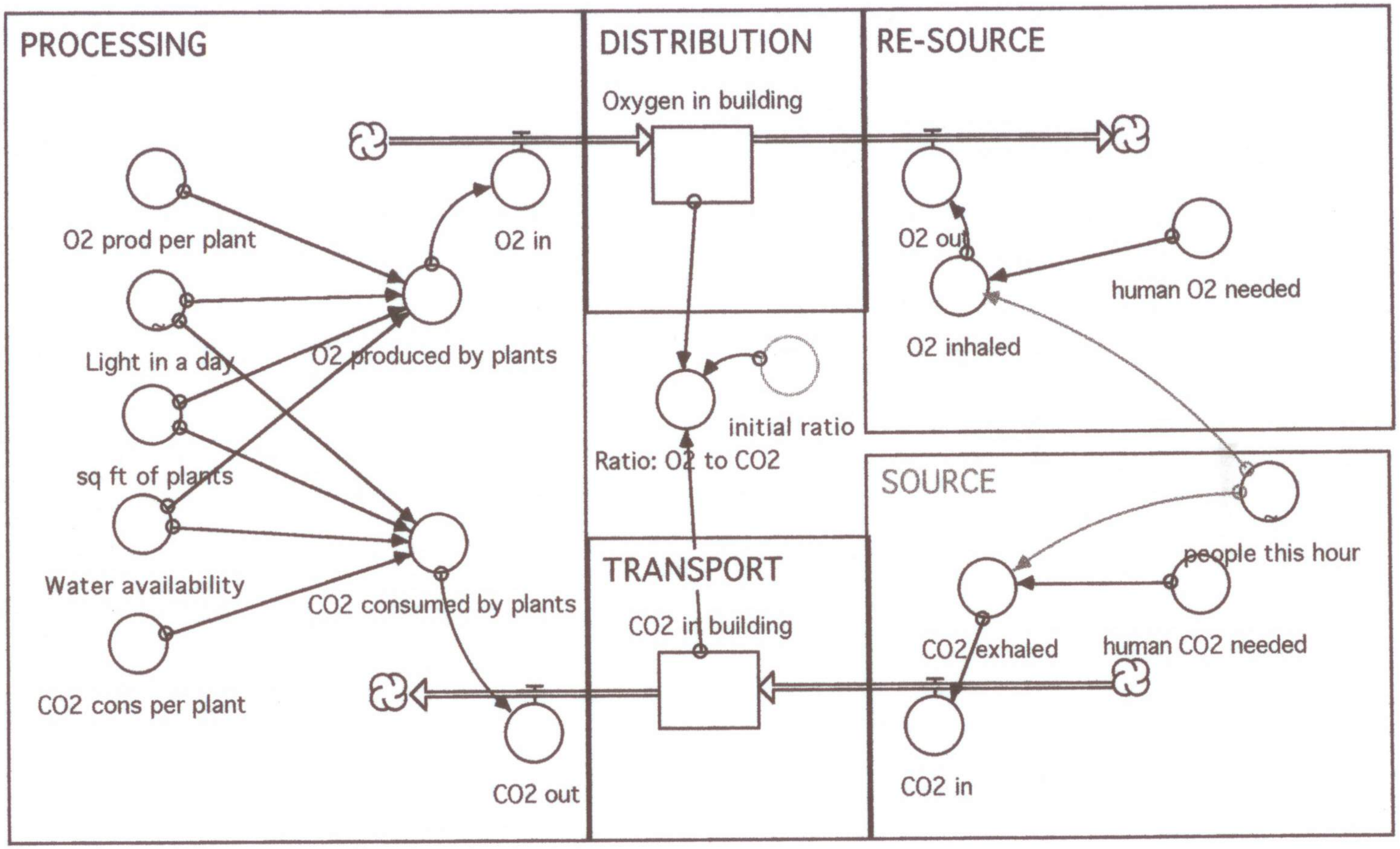
LIFE CYCLE BALANCING / AIR	FIGURE 2 AIR CIRCULATION IN A GENERIC BUILDING	NO SCALE CMPBS 1998	🟩



THREE COMPONENT BIOFILTRATION PROCESS (BY GENETRON)

LIFE CYCLE BALANCING / AIR

NO SCALE
CMPBS 1998



LIFE CYCLE BALANCING / AIR	FIGURE 4 O2/CO2 BALANCE SYSTEMS MODEL	NO SCALE CMPBS 1998

OUTPUTS: (Measured in pounds)

Initial O2 in bldg	4,485.6
Initial CO2 in bldg	974.2
initial ratio	4.6

Oxygen in building	4,323.9
CO2 in building	1,125.8
Ratio: O2 to CO2	0.834090

INPUTS:

SOURCE:

NUMBER OF PEOPLE:

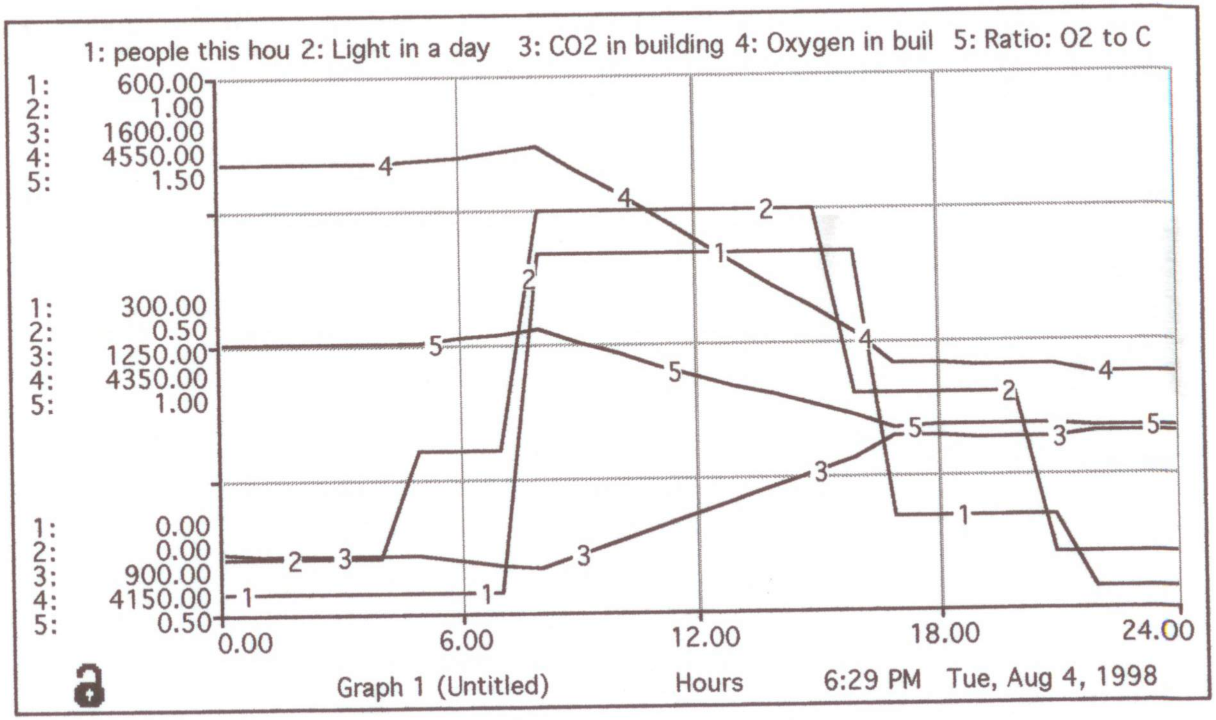
10pm - 8am	20
8am - 5 pm	400
5pm - 10pm	100

human CO2 needed	0.091667

PROCESSING:

LIGHT INTENSITY:

5am - 8am:	.3
8am - 4pm:	.75
4pm - 9pm:	.4
9pm - 5am:	.1

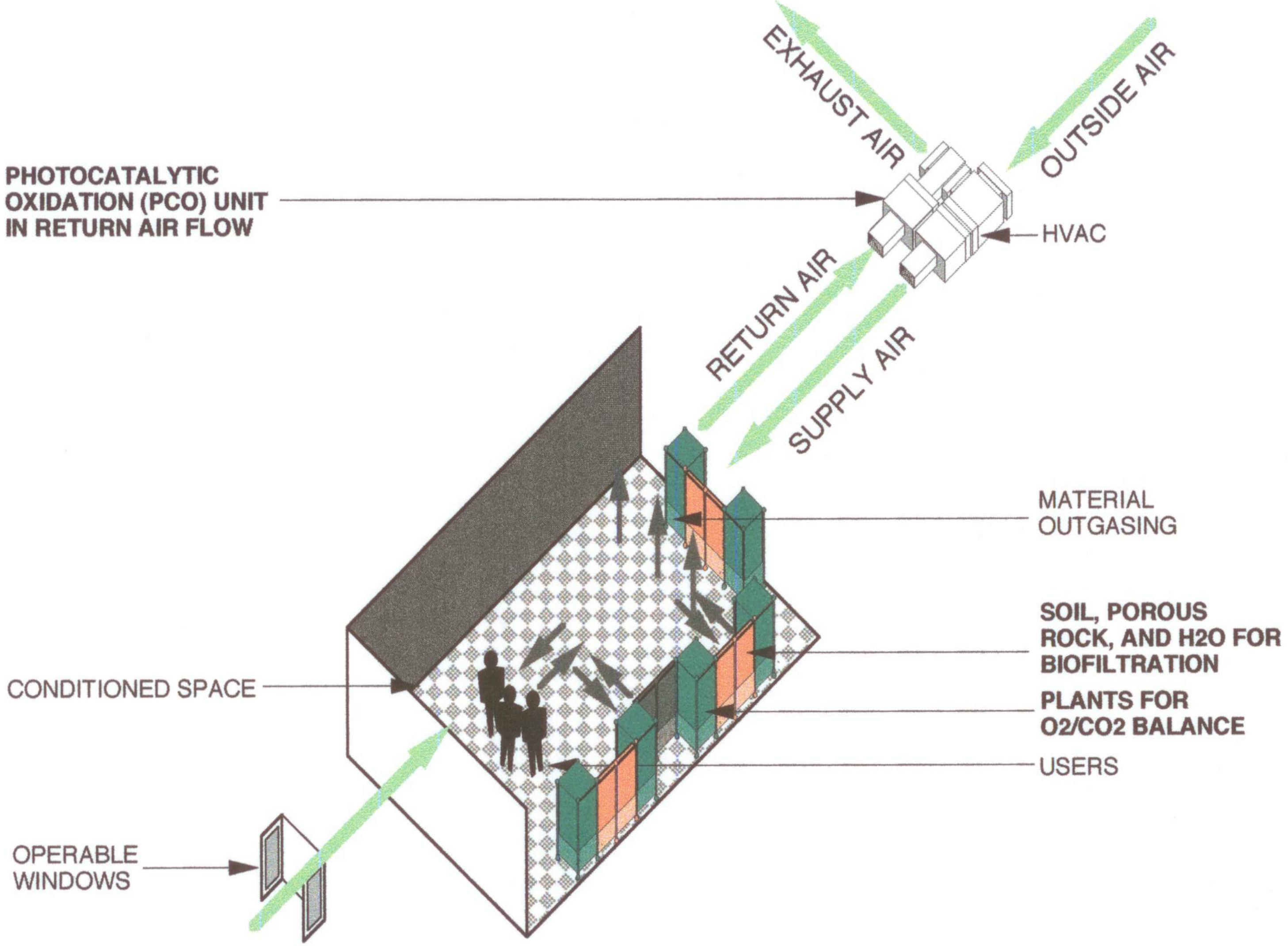


sq ft of plants	6,000.0
O2 prod per plant	0.002917
CO2 cons per plant	0.004167

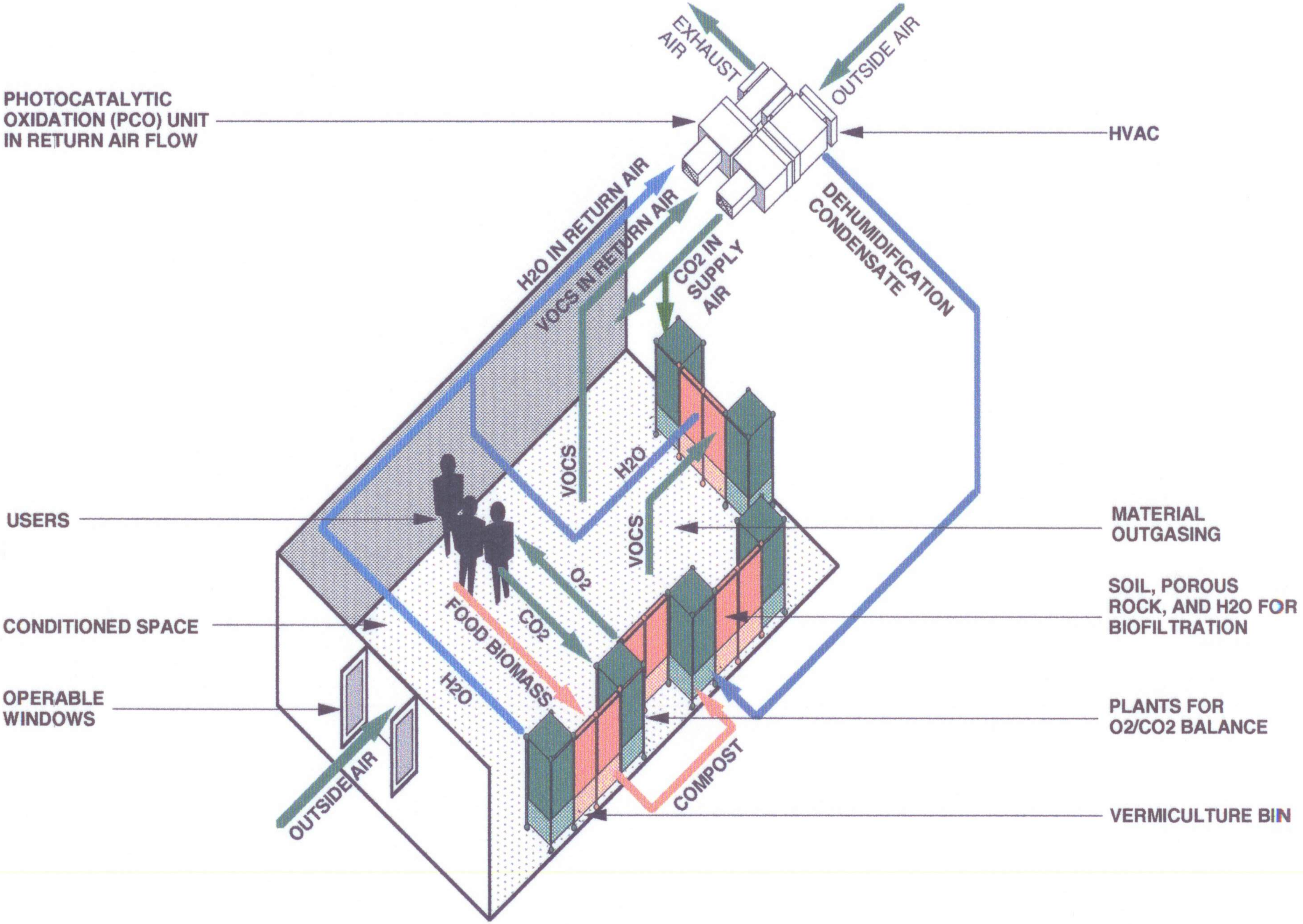
RE-SOURCE:

human O2 needed	0.077083

LIFE CYCLE BALANCING / AIR	**FIGURE 5** **O2/CO2 MODEL ONE DAY OUTPUT**	NO SCALE CMPBS 1998



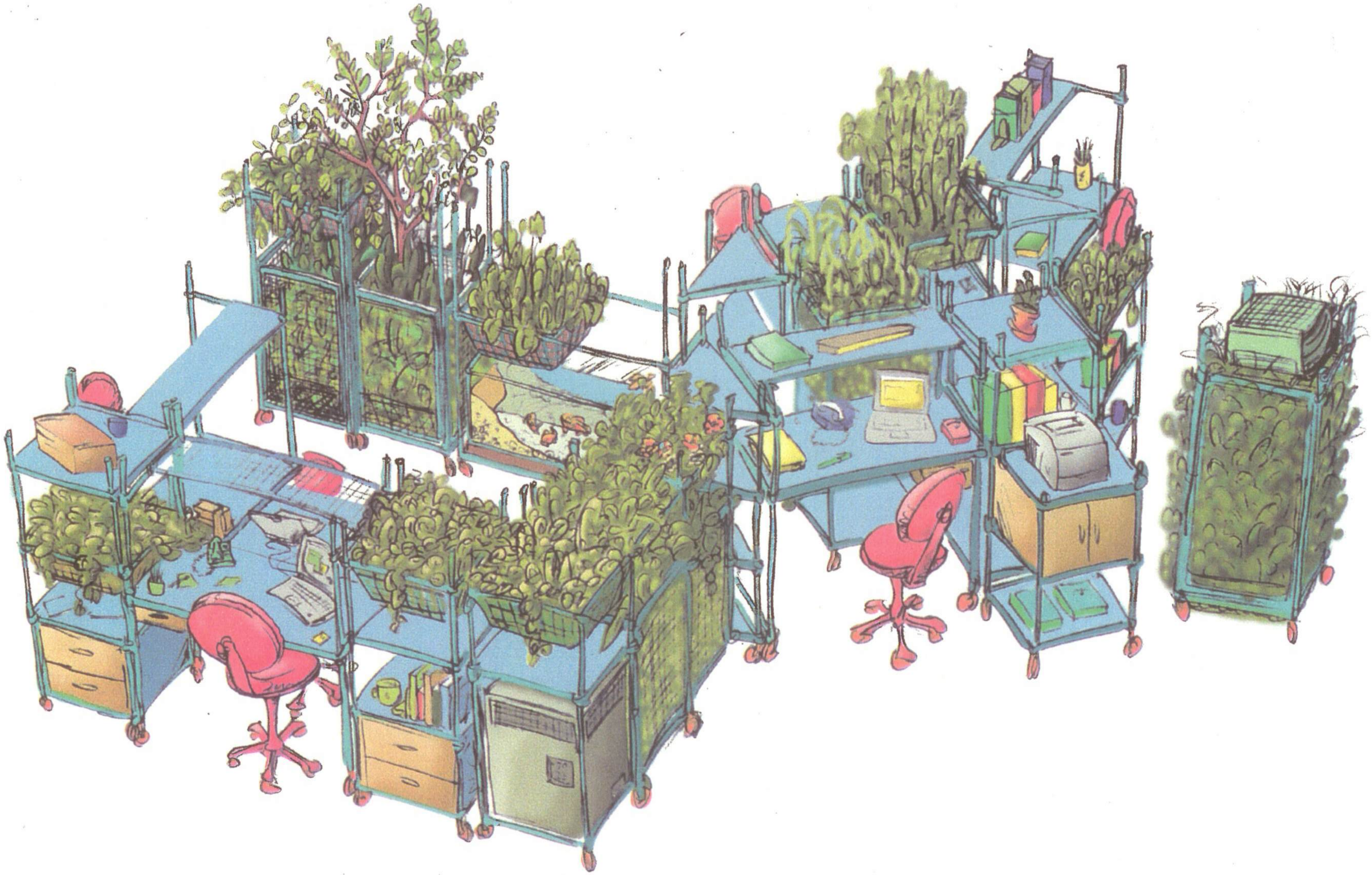
LIFE CYCLE BALANCING / AIR	FIGURE 6 O2/CO2 BALANCING AND IAQ TECHNIQUES	NO SCALE CMPBS 1998	



LIFE CYCLE BALANCING / AIR

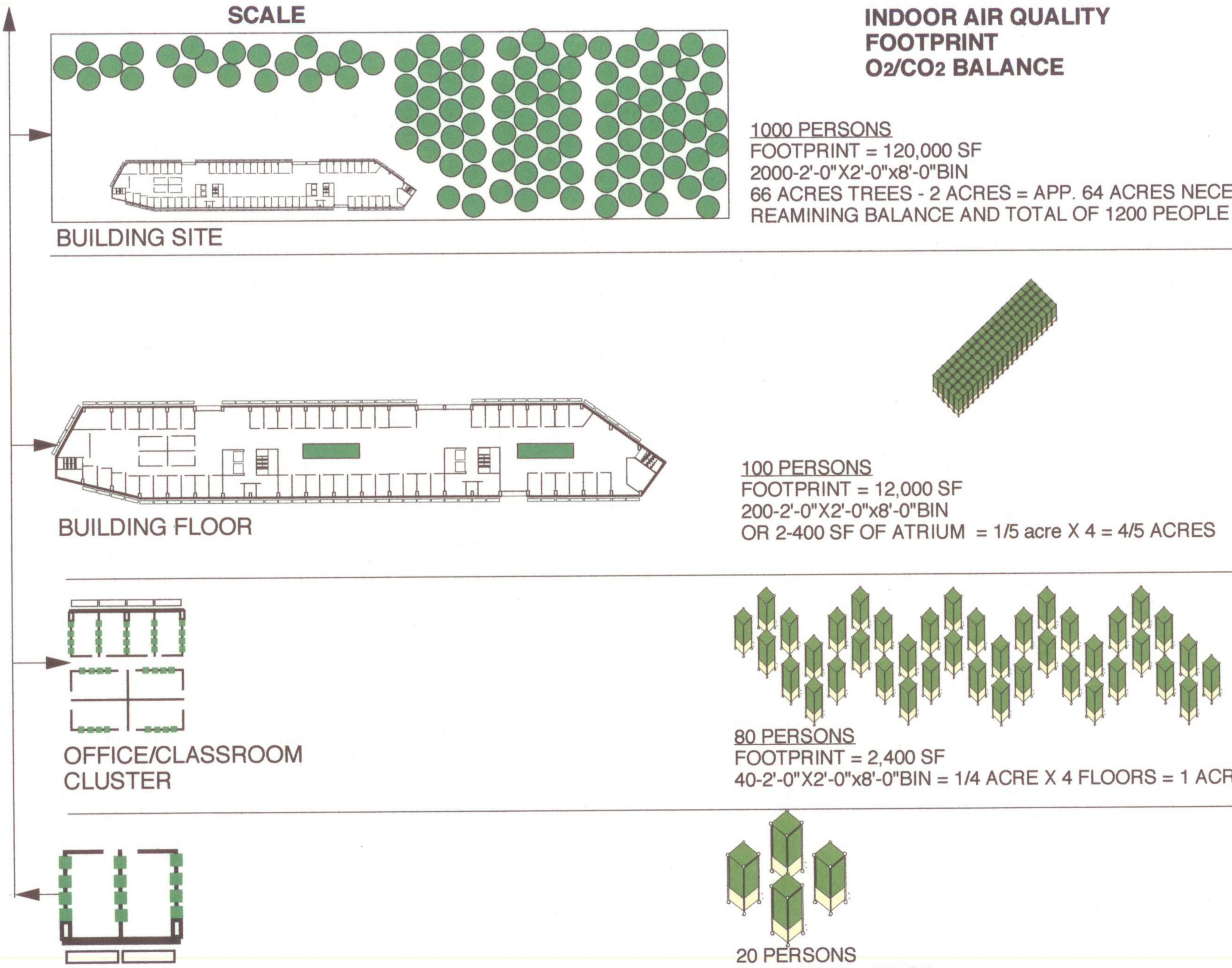
FIGURE 6
O2/CO2 BALANCING AND IAQ TECHNIQUES

NO SCALE
CMPBS 1998



LIFE CYCLE BALANCING / AIR	**FIGURE 7** **ICAT PROTOTYPE / WORKSTATION SCALE**	NO SCALE CMPBS 1998	

INDOOR AIR QUALITY
FOOTPRINT
O_2/CO_2 BALANCE



SCALE

BUILDING SITE

1000 PERSONS
FOOTPRINT = 120,000 SF
2000-2'-0"X2'-0"x8'-0"BIN
66 ACRES TREES - 2 ACRES = APP. 64 ACRES NECESSARY FOR REAMINING BALANCE AND TOTAL OF 1200 PEOPLE

BUILDING FLOOR

100 PERSONS
FOOTPRINT = 12,000 SF
200-2'-0"X2'-0"x8'-0"BIN
OR 2-400 SF OF ATRIUM = 1/5 acre X 4 = 4/5 ACRES

OFFICE/CLASSROOM CLUSTER

80 PERSONS
FOOTPRINT = 2,400 SF
40-2'-0"X2'-0"x8'-0"BIN = 1/4 ACRE X 4 FLOORS = 1 ACRE

OFFICE

20 PERSONS
FOOTPRINT = 240 SF
4-2'-0"X2'-0"X8'-0" AT 15 OFFICES = 1/6 ACRE

LIFE CYCLE BALANCING / AIR	FIGURE 8 O2/CO2 BALANCE AT DIFFERENT SCALES	NO SCALE CMPBS 1998