



# BIOSPHERE 2: A SPACE SETTLEMENT PROTOTYPE 30 YEARS AHEAD OF ITS TIME

SYSTEMS BIOLOGY FOR SUSTAINABLE LIFE OUTSIDE EARTH

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PRESENTATION OCT 24, 2020, TO  
AIAA HOUSTON – ANNUAL TECHNICAL SYMPOSIUM 2020

# WHAT IS A BIOSPHERE

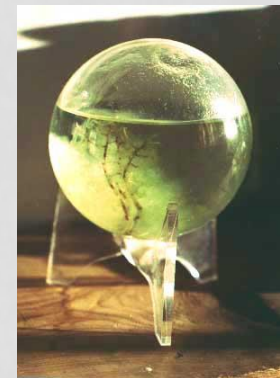
- All ecosystems inside an “enclosed” volume
- Closed system materially (or almost)
- Open system for energy and information
- Includes atmosphere, seas, geological processes
- Sustainable, self regulating given just energy input



1



2



“EcoSphere®”

# HOW SMALL CAN A BIOSPHERE BE?

- Earth (Biosphere 1) works, but is complex and hard to model
  - Many species & interactions
  - Many closed material cycles: water, carbon, nutrients, etc.  
Includes geological processes
  - Roughly self regulating over all time scales, with adaptation
    - Sun is 25% to 30% brighter than at start of life
    - Survived ice ages, warm periods, meteor impacts, rise of photosynthesizing organisms/oxygen in atmosphere, etc.
    - Individual species arrive, 99% go extinct, but Biosphere survives
- How small a biosphere could support people?

# WHY SHOULD WE CARE?

- Space settlements benefit by being as close to sustainable as possible
  - High cost of importing anything, especially from Earth
  - Risk of adequate, timely resupply
  - Expansion beyond our solar system will require long trips and bringing enough Earth with us
- We need space settlement: life on Earth is temporary
  - Biosphere 1 will be boiled off by our expanding, dying sun  
(Even if we survive other potential catastrophes like asteroids, genetically-engineered plagues, war, etc.)
  - We're maybe a third to half of the way through the useful life of the earth. We better get going!

# BIOSPHERE 2

- Engineering prototype and research tool for sustainable space settlement
  - (Unlike, say the ISS which needs resupply)
- Holds record as largest and longest-running closed environment test
  - 7.2 million cu.ft.
    - (compare: 223x pressurized volume of ISS)
  - 8 people, 3800 species
  - Sealed for 2 years starting in 1991
- Cost: around \$200M
- Facility still there (University of Arizona research lab), open to the public (and the atmosphere --no longer sealed)
- This talk is a retrospective on the experiment, the ideas behind it, and the results
- At least 30 years ahead of its time

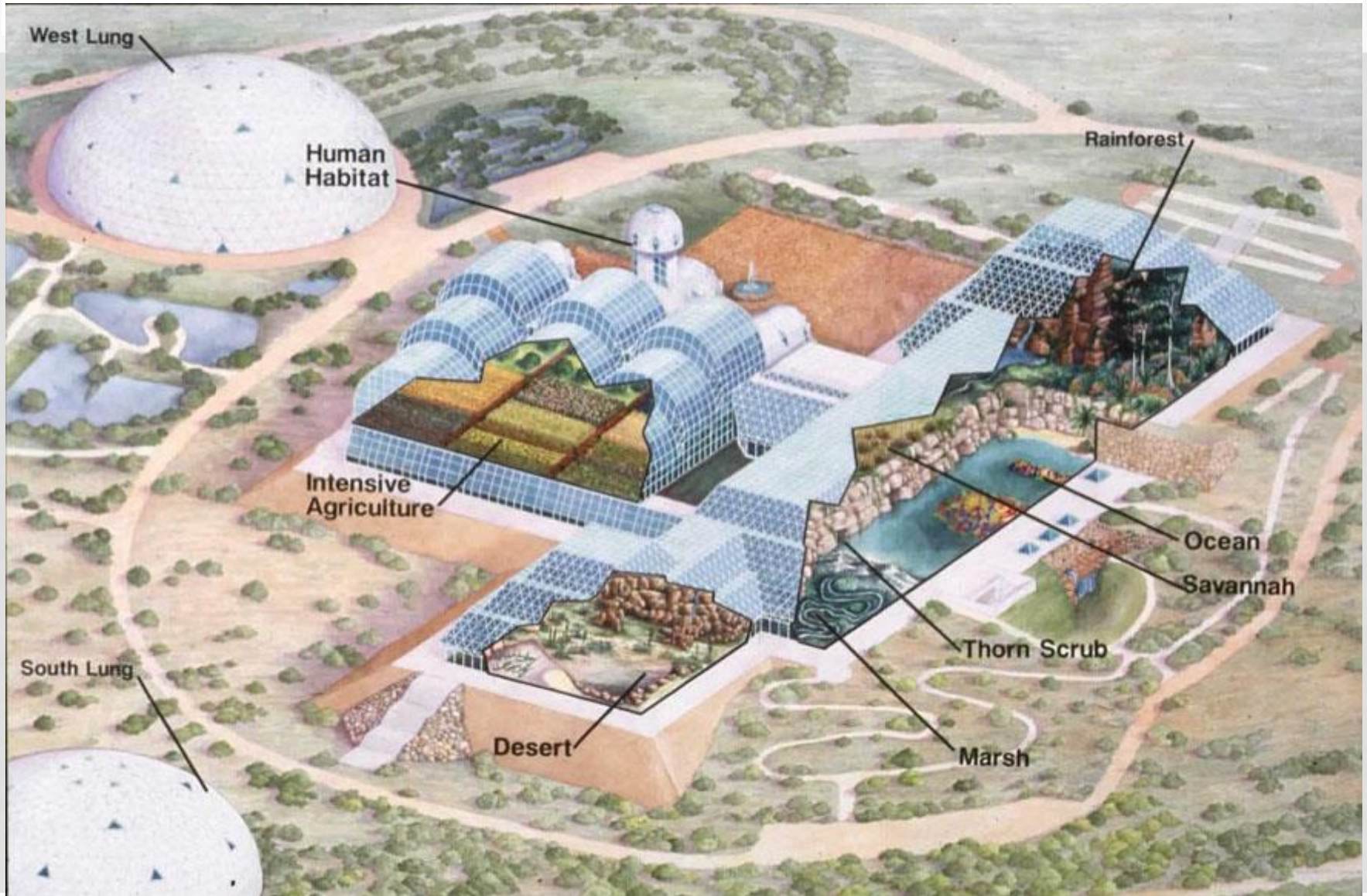
# BIOSPHERE 2 DETAILS

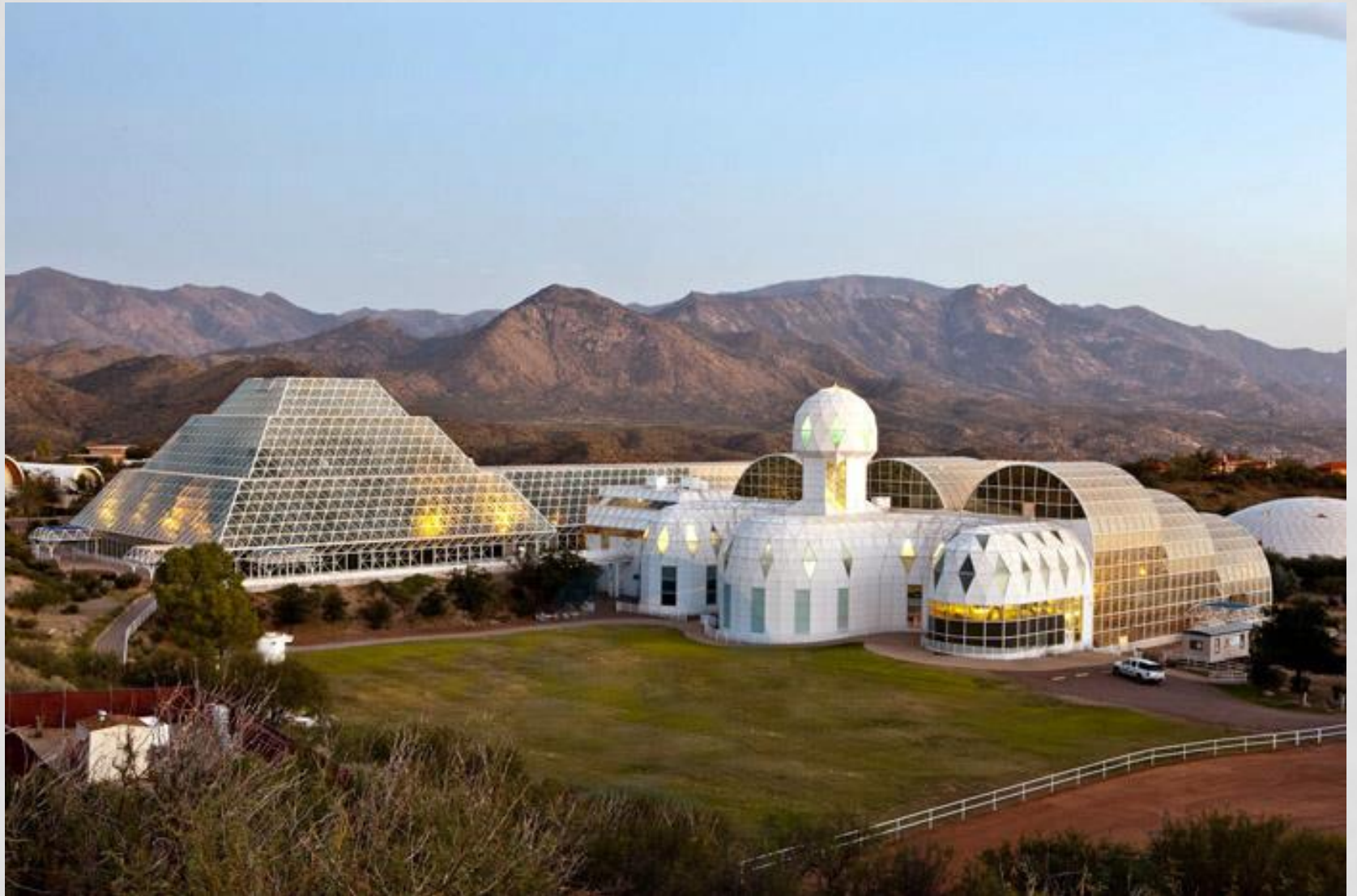
- 3.14 acre building (plus basement)
- 91 foot maximum height at rainforest
- 40 acre site by Oracle, AZ (N. of Tucson), 3820 ft. el.
  - Support buildings, cooling towers
  - Energy center with 5.7 MW backup generators, boilers, water chillers
    - Power failure: 20 minutes until plants damaged
- Closed to material flow, open to energy and information (as would be a space or Mars colony)
  - Low air leakage rate – about 10%/year
  - Energy input: passive solar, power grid with backup
  - Energy removal: cooling tower water and chilled water
  - Special sealants for 6500 windows in space frame
  - 500 ton welded stainless steel liner underneath

# BIOSPHERE 2 ORGANIZED AS 7 CONNECTED “BIOMES”

- 5 Wilderness biomes
  - Rainforest (*Amazonian, with lowlands, 50 ft. mountain, and cloud forest with misters and condensers to generate rain*)
  - Savannah (*from tropics to thorn scrub*)
  - Marsh (*Fresh → Salt, mangroves, Everglades*)
  - Ocean (*35 feet deep, 1 million gallons, with coral reef, waves, and tides*)
  - Desert (*Baja California fog desert – humid*)
- IAB (*Intensive Agricultural Biome*)
- Human habitat
- Other stuff
- ... “lungs”, and a basement, referred to as the “technosphere”

# 3D CUTAWAY OVERVIEW





# SITE OVERVIEW



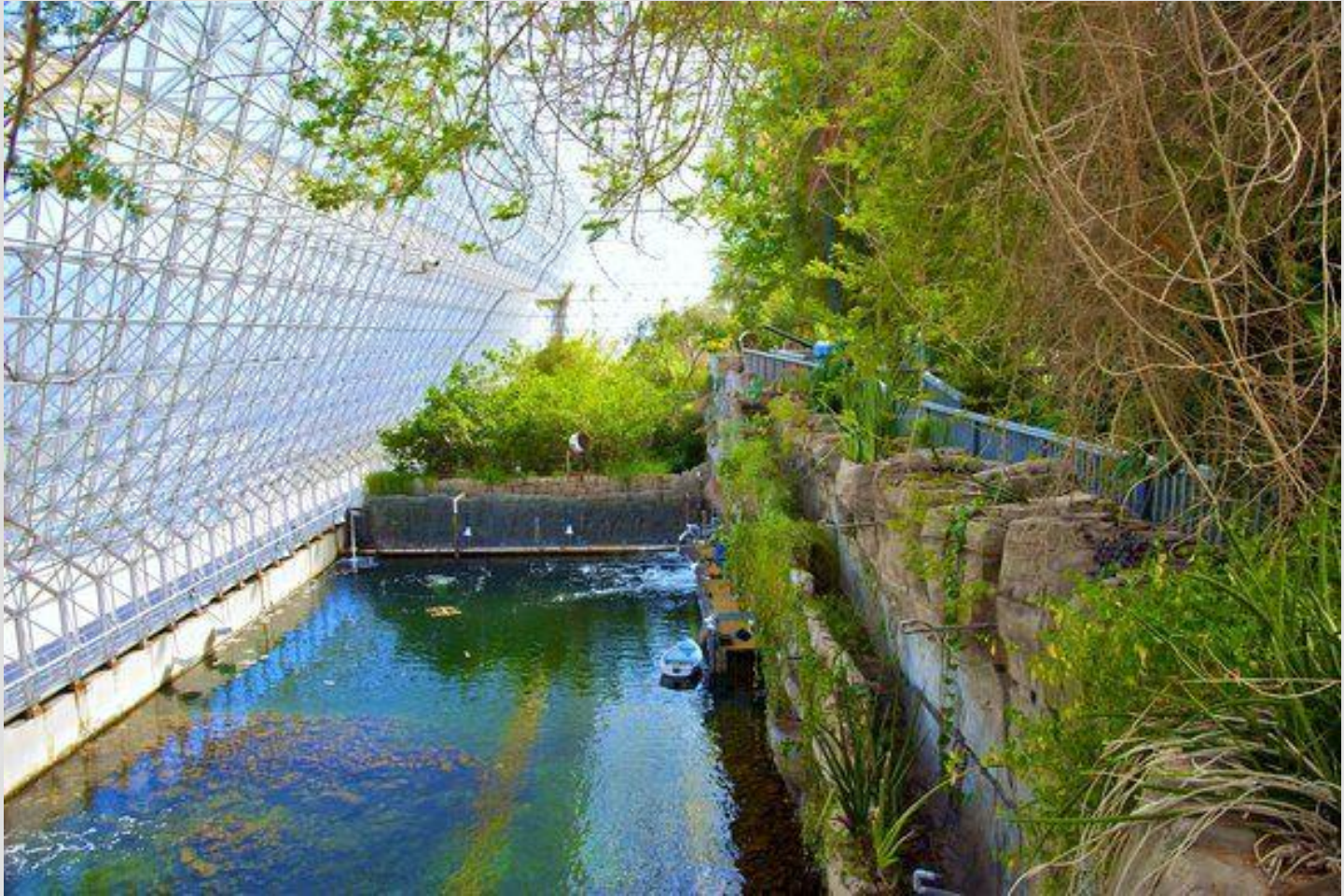
# RAINFOREST



# RAINFOREST LOWLANDS



# OCEAN, VIEW TOWARDS MARSH AND WAVE MAKER, SAVANNAH AT RIGHT



# MANGROVE MARSH, WITH TERRACING SOMEWHAT VISIBLE



# SAVANNAH TOWARDS RAINFOREST, OVERLOOKING MARSH, OCEAN



# SAVANNAH THORN SCRUB OVERLOOKING DESERT



# FOG DESERT



# INTENSIVE AGRICULTURAL BIOME (IAB)



# PYGMY GOATS



# “TECHNOSPHERE”

## A.K.A INFRASTRUCTURE IN BASEMENT

- HVAC (Heating, Ventilating, Air Conditioning)
  - 26 AHUs (Air Handling Units) – 14 large, 12 smaller cooling-only
  - Heating, cooling, condensing water for drinking and “rain”
  - Peak air recirculation rate of 1 million cu.ft./min.
- 120 pumps, plumbing, wiring
- Tanks for water storage
- Crop storage
- Machine shop
- Algae-based nutrient removal system for ocean

# TECHNOSPHERE (BASEMENT)



© CHRISTIAN BIESEL

# THE CO<sub>2</sub> SCRUBBER

- CO<sub>2</sub> scrubber secretly added very late in project
  - Chemical, not the metal oxide as in space shuttle
- Controversial when revealed later
  - Many thought it violated “sustainability” spirit of the project
  - Secrecy vs transparency issue
- Sustainability purist vs today’s pragmatist issue
  - Now, space travel is ALL “technosphere”, and we need to start introducing biology to increase sustainability
  - This project started at the other extreme: get as close as possible to a sustainable biosphere
  - Reality: future systems will be hybrid for a long time

# BIOSPHERE 2: OTHER FEATURES

- Ponds, streams, waterfalls
- Monitoring systems for air, water, soil (2500 sensors, analyzers, lab)
- Two “Lungs” (1 million cu.ft. each)
  - Provide constant pressure slightly above atmospheric
  - Avoid blowing out or imploding glass due to temperature changes (*remember the ideal gas law!*)
  - Ensure leaks are outward, not inward (contaminate experiment)
  - Like a floating roof tank
    - 16-ton aluminum disk, 4 tons of synthetic rubber membrane
    - Disk level goes up and down during the day

# SOUTH LUNG, INSIDE VIEW



# TUNNEL BETWEEN LUNG AND MAIN BUILDINGS



# HOW DO YOU DESIGN A BIOSPHERE?

- What were the goals?
- What were the constraints?

# GOALS OF BIOSPHERE 2

- Demonstrate feasibility of long-term life in a sealed environment (plants, animals, 8 people)
  - Complete material isolation: sustain air, soil, water, etc.
  - Diet with self sufficiency in food production
  - Design as a miniature version of Earth (Biosphere I)
    - Better understand earth (global warming, effect of CO<sub>2</sub>, faster recycling, etc.)
- Develop technology usable in space or on Earth
  - Technology to help settle the Moon, Mars, ...
  - Recycling technologies such as soil-bed reactors, algal scrubbers, sewage treatment, ...
  - Highly productive agriculture
  - Building techniques to minimize losses
- Study human factors of small isolated workgroups
- Tourism and education: an ecopark

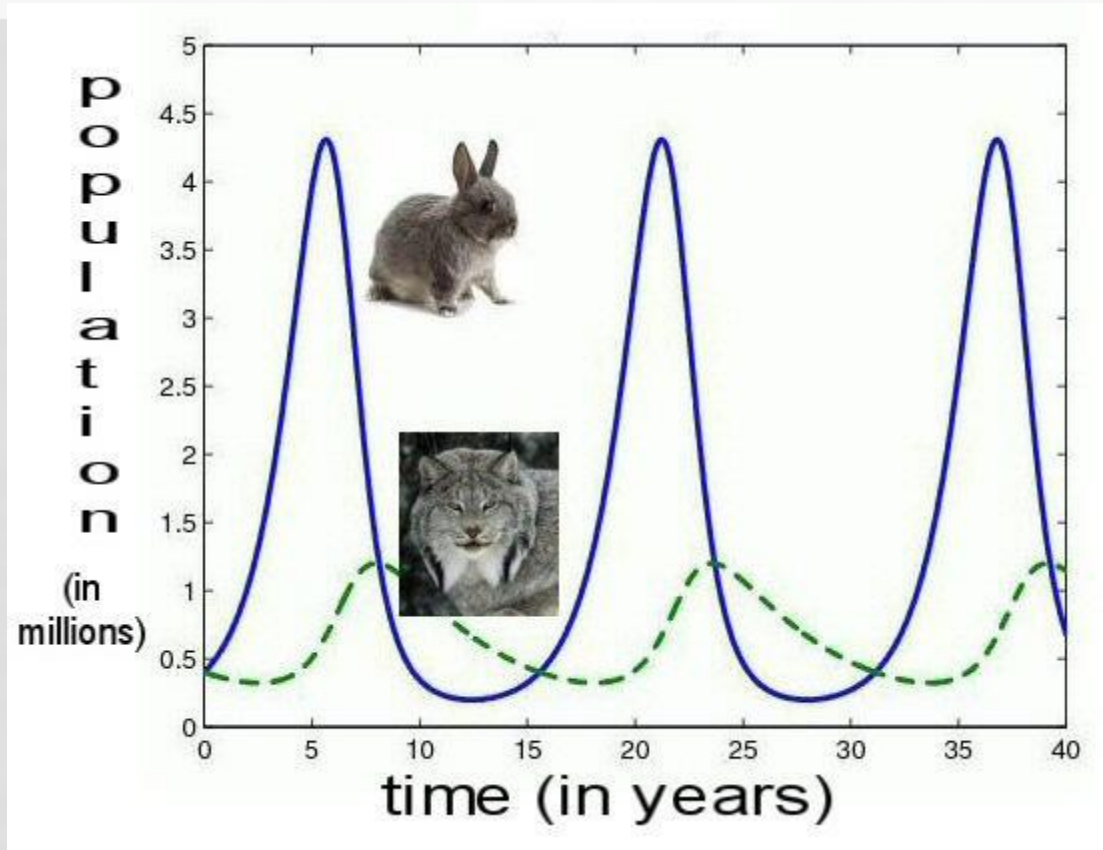
# DESIGN CONSTRAINTS - EXAMPLES

- Closed loop material cycles - EVERYTHING is recycled
  - Food self sufficiency
  - Breathable atmosphere
  - Water: drinking, waste water, irrigation, “rain”, streams
  - No toxic chemicals, including pesticides or herbicides
  - Tightly sealed to minimize exchanges with Earth
    - Positive pressure (slightly higher than outside atmospheric pressure)
    - Ensure any leaks are out of Biosphere 2, not into it
    - Avoid large pressure difference blowing out windows
- 2 years for first closure experiment, 100 year life

# TESTING THE GAIA HYPOTHESIS

- A biosphere should be self-regulating, like Earth
- Doesn't require any mystical belief – it's an emergent property of interactions among species
- Examples predator/prey cycles

# PREDATOR/PREY CYCLES HARE AND LYNX EXAMPLE



- Biosphere 2 eliminated this for large animals
  - Too much risk of extinctions with small populations
  - Humans as “keystone predator”

# SYSTEM STABILITY FOR BIOSPHERES

- Control theory has definitions of stability for systems
  - Bounded input, bounded output: allows cycles as long as they stay within bounds for given external disturbances
- Complex web of species interactions dominates
  - System behavior is determined by interactions, not just one species by itself
  - Analogous example: understanding individual neurons provides almost no understanding of what the brain does
- Different system behavior with each added species
  - Case with no predators has very different cycles
    - Too many hares, at risk of collapse in years of bad weather
    - Diseases may limit populations
- System robustness should improve with more species

# SPECIES PACKING

- Too hard to accurately model and simulate complex systems like a biosphere.
  - Accept that you'll never know everything. Then what?
- Led Biosphere 2 to “species packing”
  - If you don't know exactly what you need, fill a big suitcase!
  - Add many species, not knowing which ones will survive
  - Expect the system to self-organize, with some extinctions
  - Use some actual seawater, soil, etc. to ensure microbes, which could be considered the most important species
  - Started with 3800 species

# AGRICULTURE

## (INTENSIVE AGRICULTURE BIOME)

- 18 plots, producing 3 crops per year
- 86 crops (including herbs)
  - Beans, potatoes, peanuts for protein
  - Oats, barley, rice, wheat, millet, sorghum, maize, soybeans
  - Sweet potatoes, beets, taro, rape, mustard, safflower, tomatoes, cabbage, carrots, eggplant, peppers, leafy vegetables
  - Bananas (in rainforest), papayas, pineapple, guava, apples, grapes, strawberries, oranges, sugar cane
- Initially, animals included African pygmy goats (for milk), 35 hens for eggs, 3 pigs for limited meat, fish (tilapia grown in rice paddies)

# AGRICULTURE APPROACH

- Soil-based, not hydroponic
  - Sustainable: no separate chemicals produced elsewhere
  - Able to process human and animal waste, inedible parts of food
  - Energy efficient, proven on earth
  - Soil and marsh microbes capture toxic trace compounds
- Integrated Pest Management
  - Selection of pest-resistant crops
  - Small plots with frequent replanting of different crops
  - Variations in varieties of major crops
  - Maintaining beneficial insects
  - Manual control

# “TEST MODULE” BUILT BEFORE FULL-SIZED BIOSPHERE 2 (1986)

- 480 cubic meters (1/400) scale, about 20ft. X 20ft
- At the time, the largest closed ecology ever built
- Tested major systems
  - Feasibility of closed system, ecology of recycling, treating waste in a marsh (water hyacinth, microbes)
  - Soil bed reactors to remove trace impurities like methane
  - Technical systems (HVAC, computer systems)
  - Structure, sealants, stainless steel liner, lung
  - Agriculture: sugar cane, sweet potatoes, rice paddies, tilapia
- Closures with plants only up to 5 weeks
- Three closures with one person, up to 3 weeks (1986-1989)

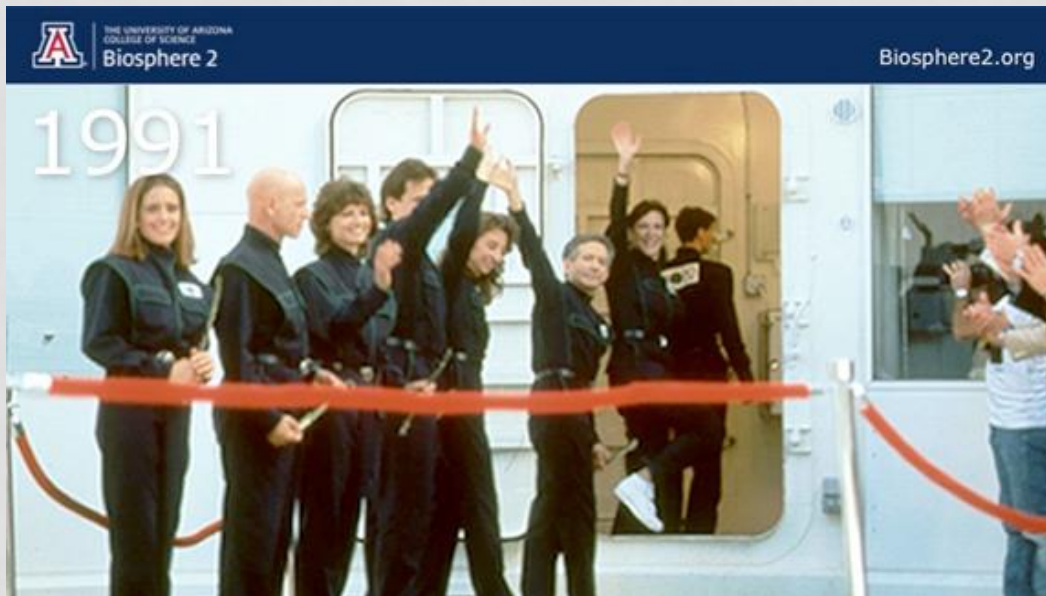
# TEST MODULE



(Not visible to right: lung)

# BIOSPHERE 2 FULL CLOSURES: MISSIONS 1 AND 2

- Mission 1: huge media event with an Indian chief, Buddhist monks, ceremonies, speeches

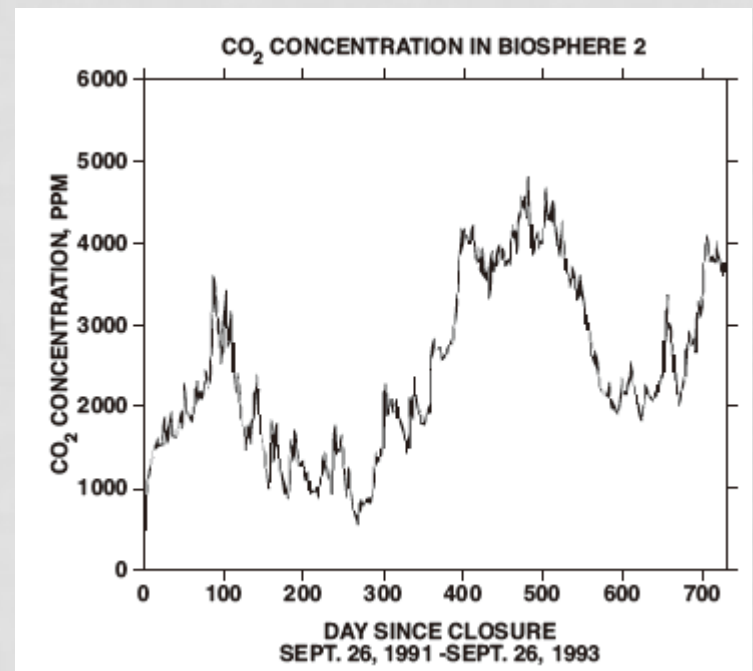


- Mission 1 (Sept. 1991- Sept. 1993) - had controversies, problems, but was completed and a lot was learned.
- Mission 2 (Mar. 1994 – Sept. 1994) ended prematurely in chaos

SO, WHAT HAPPENED IN  
MISSION 1?

# CO<sub>2</sub> WAS A HUGE CONCERN BEFORE CLOSURE, AND A MAJOR FOCUS

- CO<sub>2</sub> levels on earth 350 ppm then, 400 ppm now
- CO<sub>2</sub> levels in Biosphere 2
  - 1000 ppm in summer  
14.5 daylight hours
  - 5000 ppm maximum in winter  
9.5 daylight hours
  - 600 ppm daily fluctuation  
Due to high ratio of biomass carbon to atmospheric carbon (2 orders of magnitude vs. earth)

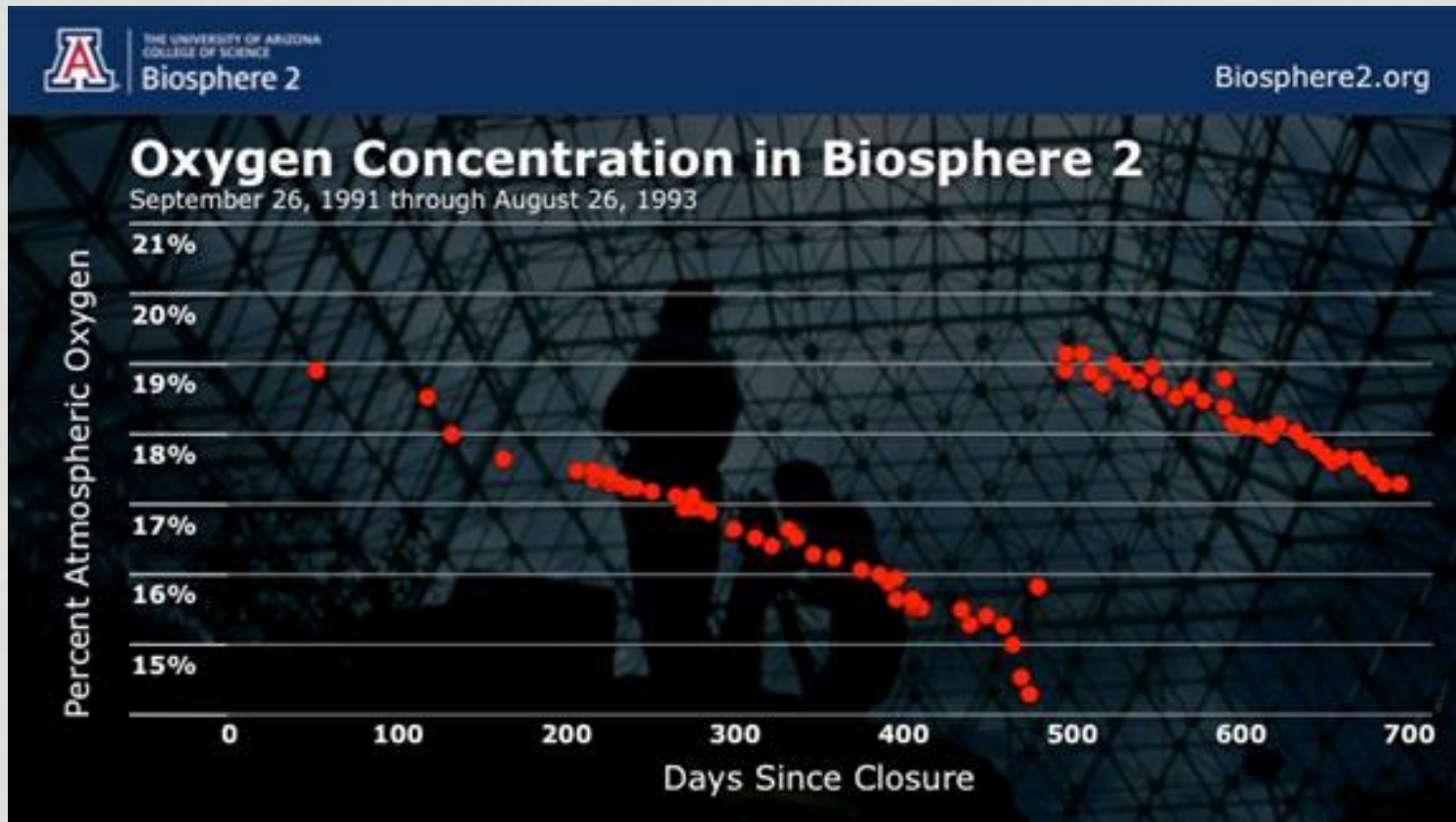


- CO<sub>2</sub> levels on Space shuttle: 5,000 ppm
- CO<sub>2</sub> levels unhealthy at 10,000 ppm

# CO<sub>2</sub> MANAGEMENT

- Lowering temperatures at night (reducing plant respiration)
- Suspending composting during low-light season
- Activating and deactivating desert and savannah by controlling irrigation
- Cutting, drying, storing biomass to sequester carbon
- Planting fast-growing plants to increase photosynthesis
- Some use of CO<sub>2</sub> scrubber in winter (100 ppm effect)
- Could be considered successful, but a lot of work
- Made harder by unusually-overcast winters, and starting with too much carbon (compounds) in the soil (more coming... )

# THE UNEXPECTED O<sub>2</sub> DECLINE



# THE O<sub>2</sub> DECLINE CAUSE

- Due to rich soil, fresh concrete
  - Unusually rich soil (high in organics) placed in Biosphere 2
  - Led to high O<sub>2</sub> consumption by soil microbes consuming it
  - Resulting CO<sub>2</sub> wasn't all absorbed by plants
  - Resulting CO<sub>2</sub> absorbed as calcium carbonate on fresh concrete
- For second mission, they coated concrete to avoid the first mission O<sub>2</sub> problem (and didn't need O<sub>2</sub> injection)
  - Soil didn't stabilize until around 1998, long after missions

# O<sub>2</sub> PROBLEM AS A REMINDER OF BIOLOGY/GEOLOGY INTERACTIONS

- On earth, calcium carbonate (limestone) was created by life (coral and marine shell), and the largest repository of carbon on earth (by far) is in rock
  - Rock (limestone, etc.) : 60,000,000 gigatons
  - Kerogens (e.g., oil, also from life): 15,000,000
  - Ocean: 38,400
  - Biomass (living and dead): 2,000
  - Atmosphere: 720
- So, as on earth, carbon went into rock, unfortunately taking O<sub>2</sub> with it.

# AGRICULTURE RESULTS

- Highly productive (claimed most efficient ever), but still not quite enough
- 81% of food was grown inside for Mission 1
  - Remaining 19% from seed stock and food grown inside system prior to closure
  - Low-calorie starvation diet – this was subsistence agriculture
  - Relied only on natural light (reduced by 50% by glass/space frame)
  - Mission 2 achieved 100%, partly by adding artificial light (high-pressure sodium lamps)
- Pigs and chickens took too much food, so were eaten

# DIET AND HEALTH

- Low calorie nutrient dense diet advocated by Dr. Roy Walford (UCLA) in previous work on diet and aging
  - He wrote the book and got to live the dream as a biospherian
- Carefully tracked entire diet by computer
- Lost 16% of their body weight in first year, stabilized and recovered some in second year
- Overall health good, improved cholesterol, blood pressure
- System supplied all vitamins except D

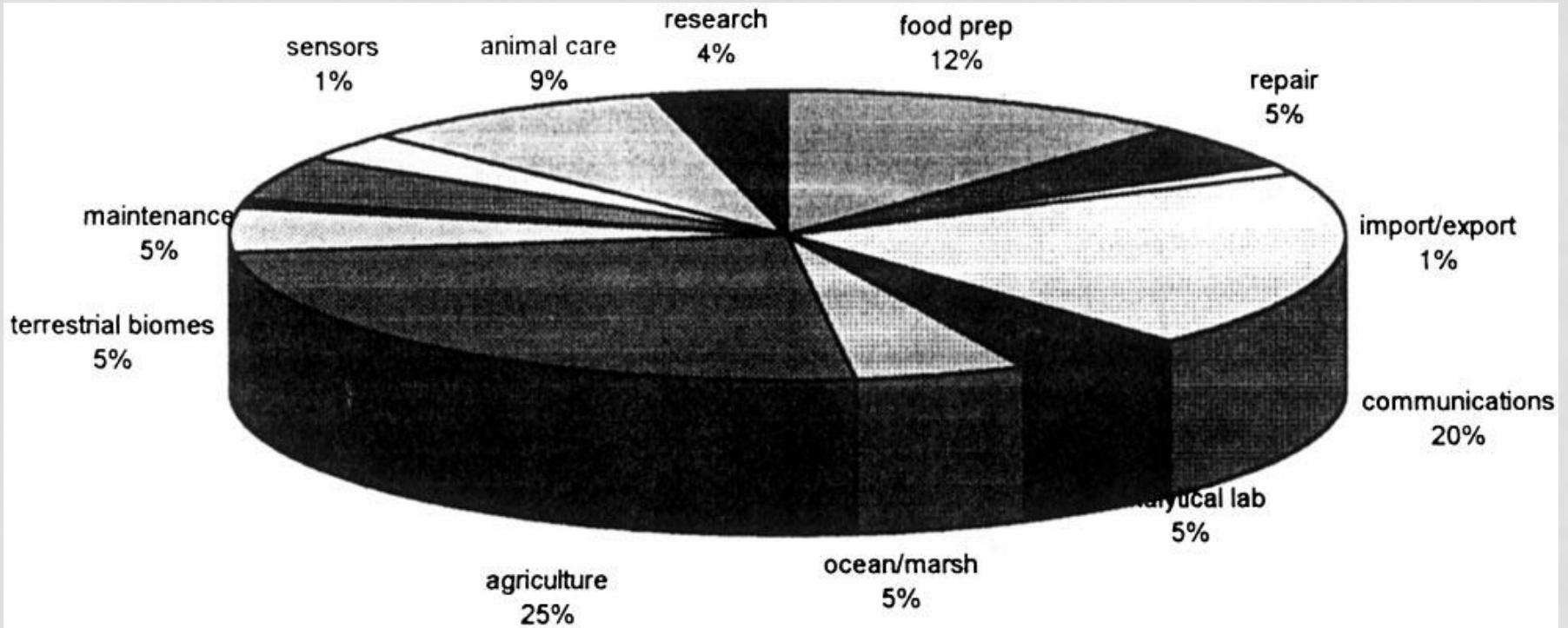
# SPECIES PACKING: SURVIVAL RESULTS

- Started with 3800 species.
  - As expected, not all survived.
  - Example: in the rainforest, 61% of 282 species of plants survived the 2 year experiment
  - Plants were individually tagged and tracked
- Proved self-organization and adaptation happens
  - Explosion of ants, cockroaches, katydids
  - Rainforest overgrown with morning glories, other invasives, requiring manual intervention
  - Rainforest grew rapidly, doubling size
  - Pollinating insects died, several bird species
  - Desert Biome shifted considerably towards species adapted to humid conditions
- Suggests the “Gaia hypothesis”, but time was too short to see all the cycles play out, and humans did have to intervene.

# OTHER SUSTAINABILITY RESULTS

- Proved feasibility of a sustainable biosphere (more or less)
  - Notable problems like  $O_2$  were explained and preventable
  - People came out alive and healthy after 2 years
    - It wasn't a given that this was possible before this
- System removed harmful compounds without toxic buildup
  - Soil bed reactors for the atmosphere, algae scrubbers for the ocean
  - $CO_2$ ,  $NO_x$ ,  $H_2S$ , ethylene,  $CO$ , methane, ozone
  - Exception:  $N_2O$ , which is normally decomposed by radiation in the stratosphere
- They were able to track and model elements in closed loop cycles
  - Accelerated cycles vs. earth, e.g., daily and seasonal  $CO_2$  cycles
- Small closed systems are vulnerable

# HOW DID THEY SPEND THEIR TIME INSIDE BIOSPHERE 2?



# GROUP DYNAMICS

- External relationships suffered
- Halfway through first mission, group had split into 2 factions, barely on speaking terms
- Power struggles outside on how to proceed were reflected inside
  - Importance of maintaining closure vs other research
  - Decisions on importing air or food
  - “Holistic” view vs. “reductionist” view of science.
- Made worse by effects of O<sub>2</sub> deprivation
  - Equivalent to elevation of 13,400 ft.
  - Fatigue, sleep apnea
- Still worked together as a team to achieve their goals
- 2 team members got married right after exiting



END

SYSTEMS BIOLOGY FOR SUSTAINABLE LIFE OUTSIDE EARTH



# SUPPLEMENTAL MATERIAL

SYSTEMS BIOLOGY FOR SUSTAINABLE LIFE OUTSIDE EARTH

# WHY PUT A GREENHOUSE IN THE ARIZONA DESERT?

- Photosynthesis is key to maintaining O<sub>2</sub> & CO<sub>2</sub>
- Glass blocks ultraviolet light, part of “PAR” – Photosynthetically Active Radiation
  - Glass and the space frame structure block about 50%
- So, a lot of sunlight/clear sky is needed
  - Want many days without clouds, rain, haze, smog
  - Higher elevations of Arizona are perfect!
  - Outweighs the additional costs of air conditioning (and some heating in winter)
- At first, they didn't consider artificial lights
  - Despite the fact that on Mars there's less sunlight, and you'd need to mostly be buried to avoid radiation anyway

# BIOSPHERE 2 PROJECT MILESTONES THROUGH MISSION 1

- Space Biospheres Ventures (SBV) started July 1984  
Owned by Decisions Investment (Ed Bass), initial \$30M
- Conference on vision and feasibility: Dec., 1984  
Signed up outside scientific advisory committee
- Basic design & engineering done: 1986
- Test module construction done: 1986
- Test module closed experiments: 1986-1989
- Construction start: Jan, 1987
- Support buildings completed: Mar., 1989
- Plants, animals, agriculture in place before closure
- 9 one-week test closures before Mission 1
- Mission 1: closure (8 people): Sep. 1991 – Sep. 1993

# BIOSPHERE 2 MISSION 2 ENDED IN CHAOS

- Mission 2 started March, 1994, intended 10 months
- April 1994: dispute led to ousting of management
  - Federal marshals and police arrived with restraining order, took over the site, stopped communications
  - Ed Bass hired Steve Bannon (!) to run SBV
  - Two members of first crew broke in, unsealed the airlock, broke some windows
  - Team captain quit to join wife (the suspended SBV CEO)
- Many in the Scientific Advisory Committee quit
- June, 1994 SBV dissolved
- September, 1994: Mission 2 ended prematurely
- Scientific credibility at an all-time low at that point

# AFTER THE MISSION 2 CHAOS

- Columbia University ran it 1995 - 2003
  - Biosphere 2 modified from closed system to open air flow
  - No longer applicable for space habitats- focus on earth: e.g., CO<sub>2</sub> effects on plants & ocean acidification
- Offered for sale in 2005 by Decisions Investments Corp (Ed Bass)
- Sold briefly to a real estate development company in 2007, leading to fears of subsequent demolition
- University of Arizona took over running it in 2007
- University of Arizona assumed ownership in 2011
- Various earth science & farming experiments ongoing
  - None sealed, but large, nearly-isolated facility is unique

# THE MONEY

- Privately funded (Ed Bass – Texas billionaire)
- SBV (Space Biospheres Ventures) set up as a for-profit corporation, initial \$30M
  - Expected to sell technology
  - Tourism & education – ecology theme park
- Up through first 2-year experiment, estimates of \$150M - \$200M
- Rumored yearly cost to run: \$25M, of which \$16M are energy costs
  - This is, after all, a greenhouse in the Arizona desert!
- Unnamed source on Wikipedia put total cost at \$200M by 2007

# HUMAN HABITAT

- Private apartment for each biospherian with upstairs and downstairs, shower & toilet (but no toilet paper – bidets were used)
- Kitchen, meeting area, recreation facilities, exercise room, communications center
- Lab space, medical clinic

# HUMAN HABITAT (MEETING ROOM)



# KITCHEN



# EXAMPLES OF SOME OF THE SPECIES PLACED IN THE WILDERNESS BIOMES

- Hummingbirds, bees, bats, moths, butterflies
- Snakes, reptiles, turtles, 40 geckos, 50 toads
- Ants, termites, cockroaches
- Predators for mites, mealy bug, cockroaches, pillbugs
- Oysters, crabs, coral
- Agave, jojoba, rubber trees, mosses, ferns, trees producing gum and soaps.

# DAISYWORLD: A TOY “DEMO” OF THE GAIA HYPOTHESIS

- A simple mathematical model of a “toy world”
  - Sun whose output is rising over time
  - Only 2 species: black daisies and white daisies
- Temperature regulation based on balance between black daisies and white daisies
  - Black daisies
    - absorb more light, warm the planet
    - do better at low temperatures because they get warmer
    - die off at higher temperature because they get too warm
  - White daisies
    - reflect more sun, cooling the planet
    - do better at higher temperature because they stay cooler due to reflecting the sun

# SOME TEST MODULE RESULTS

- First facility to use biological means to simultaneously purify air (vs. catalytic burners), completely recycle water & human waste, remove toxic trace compounds
- Tested and modified technology
  - Leak rate of 24%/year
  - Estimated parameters in dynamic simulation models for O<sub>2</sub>, CO<sub>2</sub>
- Some food grown
  - Soil-based rather than hydroponic,
  - Not enough area for sustaining long-term human habitation

# BREAKING THE SEAL: THE MISSING FINGERTIP AND THE DUFFEL BAG

- 12 days into mission, Jane Poynter had a threshing machine accident, cutting off the tip of her finger
- Evacuated for medical attention
- Returned hours later with a duffel bag
  - She claimed it only had spare parts and plans
- PR disaster, media claiming experiment was compromised, bringing in food, letting in air
- *(The lead programmer had a \$1000 bet with a biospherian that Biosphere 2 would be opened within 100 days)*

# THE UNEXPECTED O<sub>2</sub> DECLINE

- Rapid, steady decline in O<sub>2</sub>, without correlated CO<sub>2</sub> increase
  - 20.9% down to 14.5% after 16 months
  - Equivalent to being at 13,400 ft.
  - Unknown reason at the time, not seen in test module
  - Led to fatigue, sleep apnea
- 2 unusually dark, overcast el-Nino winters weren't the cause, but didn't help
- 31,000 lbs liquid O<sub>2</sub> added, returning atmosphere to 19%: Jan, 1993
- Another PR disaster!

# WERE THEY A CULT?

- Well, maybe yes, to some extent...
  - Close-knit group for many years
  - Based on shared ideology and vision of going to Mars
  - Important roles closed to outsiders
  - Closed meetings, lots of rumors about what went on
  - John Allen, the leader, ran a commune in New Mexico (Synergia), and a theatre group (“Theatre of All Possibilities”)  
Accusations of psychological humiliation, corporal punishment
- Accusations were somewhat overblown
  - “doomsday cult”, “western civilization is over”, “just a failed theatre group”, etc.
- Accusations definitely hurt their scientific credibility

# MAYBE YES, KIND OF, BUT...

- Accusations of lack of scientific training were overblown
  - There was expertise in their group, at least some with appropriate degrees
  - They tapped and managed outside scientists, expertise as well.
- While there was some weirdness, this was a serious project
- That's probably what it took to get this unusual project done

# MONITORING SYSTEMS

- 2500 sensors and automated analyzers, plus manual lab
  - Temperature, pressure, humidity, wind velocity, flow, water levels, fan status, pump status, power, PAR, etc.
  - Chemical compounds: CO, CO<sub>2</sub>, O<sub>2</sub>, O<sub>3</sub>, NO<sub>x</sub>, N<sub>2</sub>O, NH<sub>3</sub>, H<sub>2</sub>S, SO<sub>2</sub>, CH<sub>4</sub>, total hydrocarbons, for air, potable water, other water, soil
- 15 internal and external networked computers
- “Global Monitoring System”
  - Computerized monitoring, analyzing, and storing data
  - Automated and manual chemical analyzers for air & water
  - Health of the computers and networks
  - Comprehensive diagnostics postponed, never implemented

# CONTROL SYSTEMS

- Control temperatures, humidities, wind velocities
- Control via Air Handling Units (AHU's)
  - Flows of cooling tower water and chilled water
  - Steam heating flow (heating, and reheat for humidity control)
  - Throttling of inlet air flow to blowers
- Challenges
  - Wanted tight control – scientific experiment, not a house
  - Significant variations in targets across biomes, heights
  - Sun/shade variations inside
  - Weather variations outside (sun/shade , day/night)
    - All-glass, without shade, louvers, or tinting, for photosynthesis
    - Cloud passing overhead caused noticeable changes
    - Hot summer sun, winter snow
  - Interactions between AHUs & biomes due to shared cooling water
  - Interactions between biomes due to open air boundaries
  - Need for condensation for potable water and utility water
  - Sensor & valve reliability
  - Graceful degradation with failures. Only some spare parts.

# CONTROL SYSTEMS (CONTINUED)

- Optimization goals: economics and constraints
  - Humidity maximums, air velocity min & max
  - Cooling tower water cheaper but less effective than chilled water
  - Number of AHUs used and airflow at each
  - Supervisory control for optimization, startup sequencing
- Initial proposals used industrial-style controls
  - Temperature to energy flow cascade controls (feedback)
  - Feedforward for solar input energy and history, between biomes
- Subcontractor never got sensors, valves, low-level controls to work very well
  - Local builder with little understanding of control systems
  - Abandoned tight control, optimization
  - Ended up with a set of templates for targets for simple controllers for different conditions

# EARLY PROTOTYPE TOP-LEVEL GLOBAL MONITORING SYSTEM DISPLAY

Biosphere large overview

7 Aug 93 4:34:10 p.m.



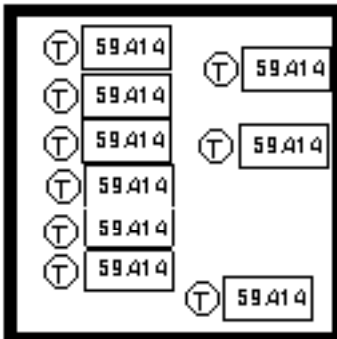
COOLING-WATER-CIRCUITS



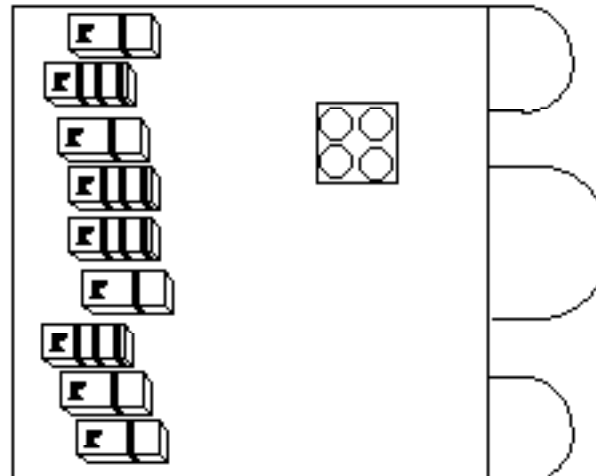
POTABLE-WATER

AIR-QUALITY-MONITORING

WATER-QUALITY-MONITORING



DESERT



IAB

1/4 scale

1/2 scale

3/4 scale

Full scale

LOWER-SAVANNAH

SAVANNAH

⊕ 59.414

⊕ 59.414

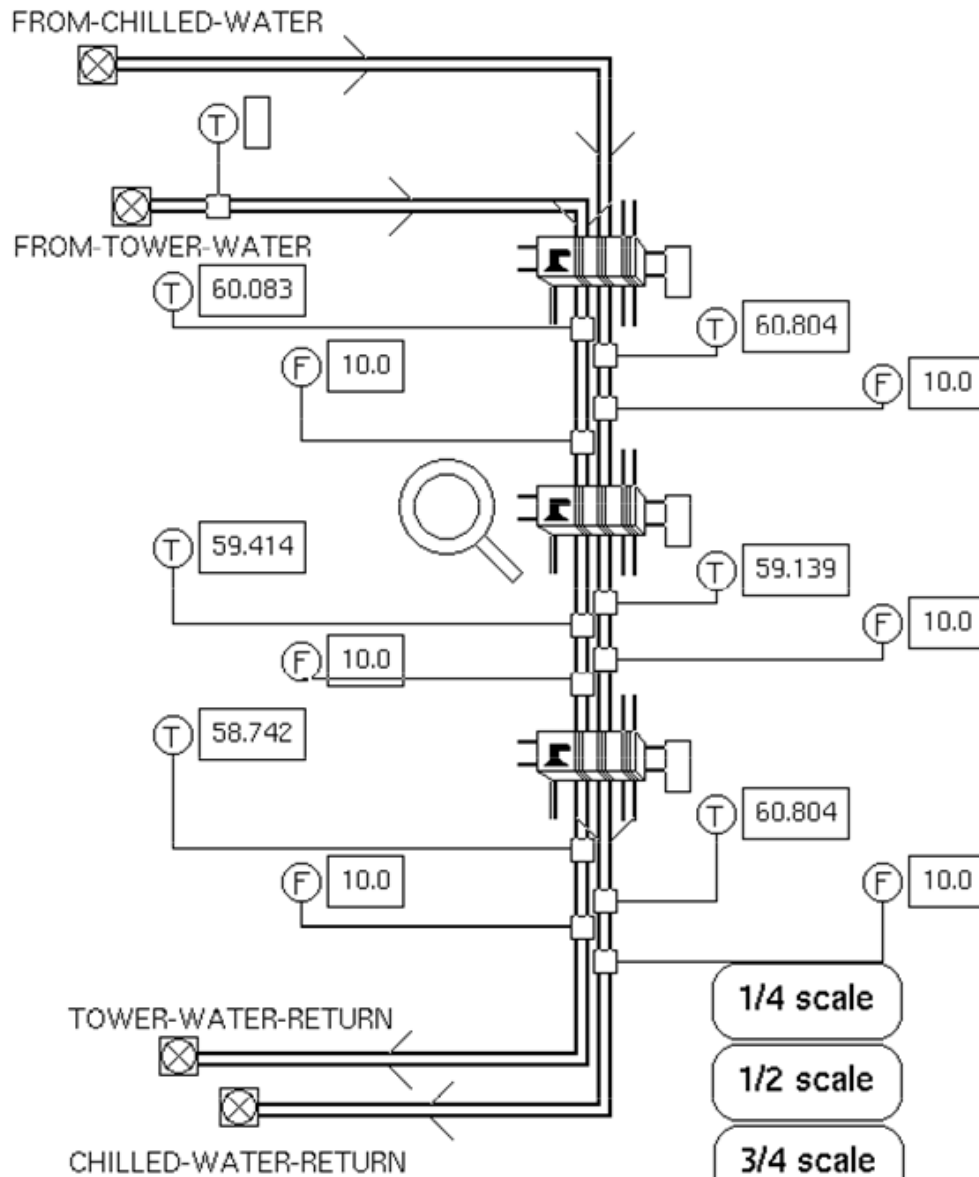
MARSH

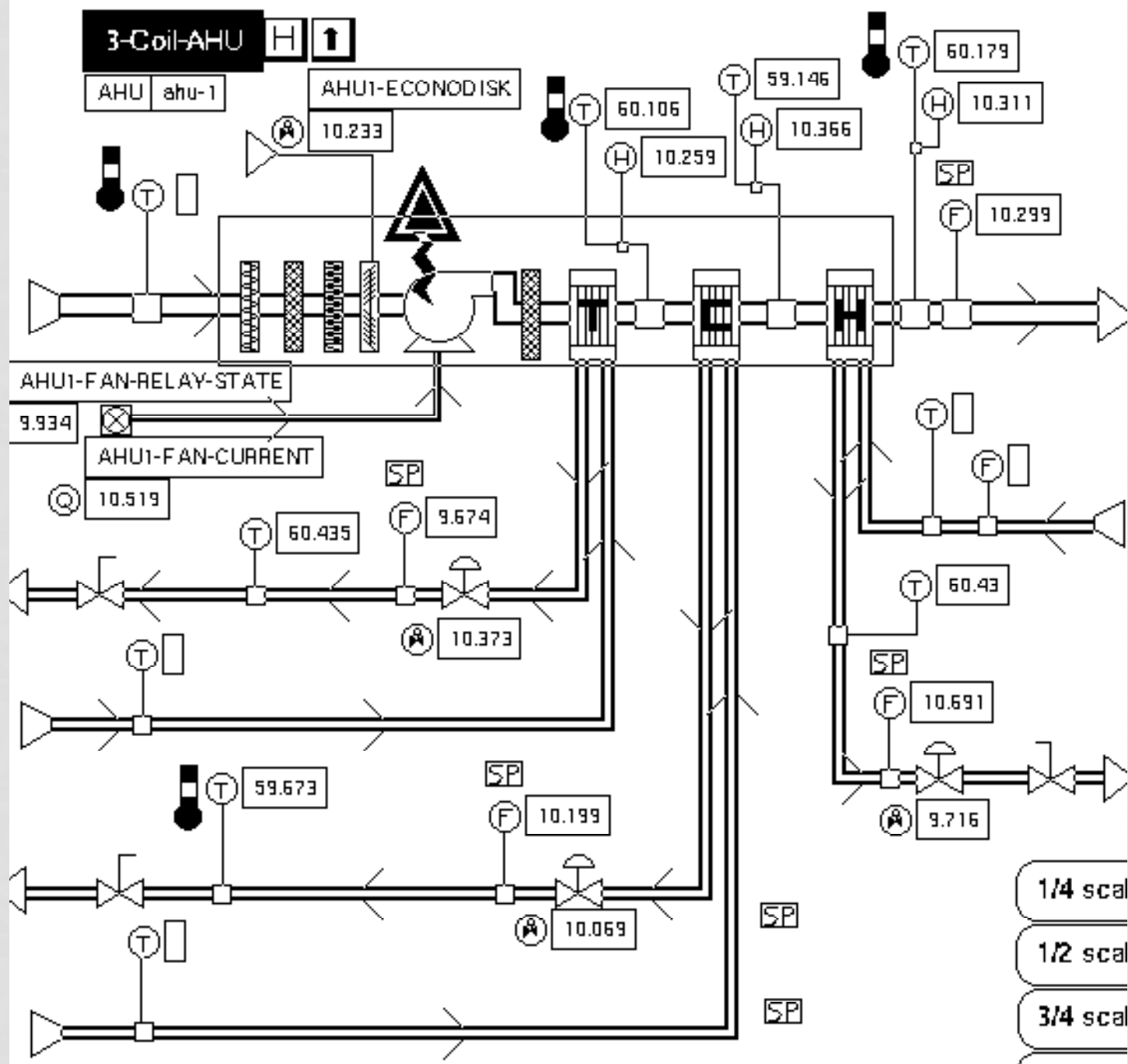
OCEAN

RAINFOREST



# EXAMPLE COOLING SUBSYSTEM





1/4 scal

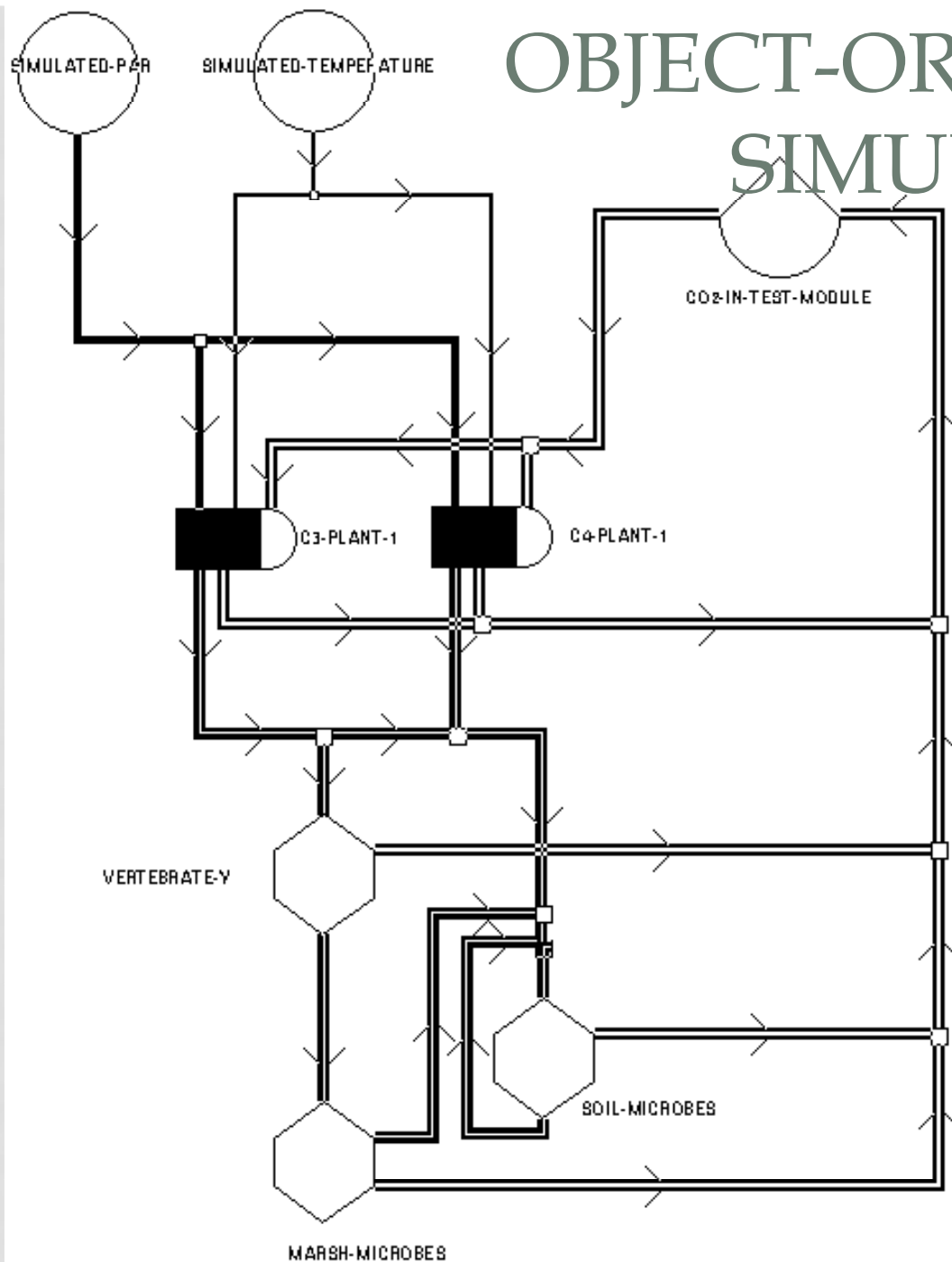
1/2 scal

3/4 scal

# SIMULATION FOR TEST MODULE EXPERIMENTS

- Biological system dynamic simulation
  - Focus on  $O_2$ ,  $CO_2$ , etc.
  - Biological objects following Odum's ecology textbooks
    - "Primary producers" (plants)
    - "Decomposers", others
    - Differential equations associated with each type of object
  - Flows of material and energy as connections between the objects
  - Parameter estimation to match test data to simulation
  - Work mostly by University of Arizona

# OBJECT-ORIENTED SIMULATION



# EXAMPLES OF VARIABLES TRACKED IN SIMULATION

C3 photosynthetic rate	****
C4 photosynthetic rate	****
Marsh microbes base respiration	****
Soil microbes base respiration	****
vertebrate-y respiration	****
Night-temperature	****
Minimum day temperature	****
Max daytime temperature increase above mean	****
Minimum day par	****
Max daytime par increase above mean	****

# ANNOUNCEMENT TEXT

Biosphere 2 was a unique experiment in a materially closed ecological system, as a prototype for sustainable space settlement. It was at least 30 years ahead of its time. When 8 “biospherians” were sealed in the 3.14 acre facility for 2 years starting in 1991, it was (and remains) the world’s largest and longest-running closed environment test. The facility is still there and open to the public, although it is no longer sealed.

This talk is a retrospective on the experiment, the ideas behind it, and the results.

# THE SPEAKER

The speaker, Dr. Greg Stanley, was involved in the Biosphere 2 project as a consultant, mainly in 1989-1990, and was present at the first closure in 1991. He led the work done there by Gensym, providing computerized monitoring, control, and some dynamic simulation.

Dr. Greg Stanley creates, develops, and manages innovative technology, especially based on artificial intelligence. He created computer applications for users as diverse as the Iridium satellite communications network, AT&T, Biosphere 2, ExxonMobil, the Abu Dhabi National Oil Company, Saudi Aramco, a Japanese nuclear industry/government consortium, and BMC. Applications include fault diagnosis, process automation and control, dynamic simulation, and network management. He worked at Exxon in technical and management roles in process control, engineering, IT, artificial intelligence, and dynamic simulation. He built products and managed product development at Gensym, the leading provider of real-time expert systems. He helped product development for software and engineering companies such as SAT, BMC, SmartSignal, and Integration Objects. Technical specialties include chemical engineering, artificial intelligence, fault diagnosis, process control, dynamic simulation, network management, and estimation theory such as data reconciliation and Kalman filtering, as well as product architecture and software development to implement these applications. Greg has a PhD in Chemical Engineering from Northwestern University, and a BS in Chemical Engineering from Purdue University. He has published over 25 peer-reviewed technical papers.

Other technical material is available at the Greg Stanley and Associates/ Performity LLC site:

<https://gregstanleyandassociates.com/whitepapers/whitepapers.htm>

Other space settlement related material is available at

<https://performity.com/Resources/Space/space.html>