Space Manufacturing Facilities

Space Colonies

AMERICAN INSTITUTE OF AERONAUTICS AND ASTRONAUTICS

4. Closed Ecosystems of High Agricultural Yield

H. Keith Henson and Carolyn M. Henson
Analogue Precision, Inc.

Abstract

The mass of a space farm can be reduced by using agricultural techniques which eliminate the need for soil, making it more feasible to grow conventional foods. The authors propose that human nutritional needs in space can be filled abundantly in conventional ways. The area and biomass requirement for the grains, fruits and vegetables of the proposed diet are computed to be 22 m^2 and 96 kg per person. Rabbits are found to be efficient meat producers, requiring 10 m^2 of photosynthetic area per person for feed. Biomass per person for meat production is computed to be 40 kg. With no additional photosynthetic area and with a biomass of 21.5 kg, agricultural and kitchen wastes will feed goats and chickens to provide milk and eggs. Total photosynthetic area per person would be 32 m^2; and total biomass, including water, would be 200 kg per person. There is reason to believe that the agricultural production of a space farm will be more stable than that of an Earth farm.

An integrated system is proposed to recycle waste materials, fix nitrogen, and maintain air quality. The concept is presented of building the construction site facility of material containing elements later required in Model 1, but not available from the Moon. A "first pass" design for a construction site facility based on the space farm area requirements is presented. Labor requirements for the space farm should not be excessive, and such work may provide recreation for the workers.

Introduction. This paper explores the potential for an agricultural system in space, hereafter called the "space farm." The parameters used are those of the construction site for Model 1. Farming on Model 1 itself, when completed, will be much easier (more area per person). Farming on the Moon will be much more difficult due to intermittent light. However, much of the information contained in this paper should apply to these other environments.

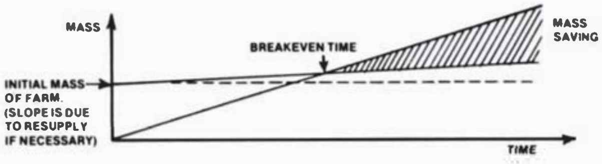
The merits of the space farm may be evaluated by linear programing, illustrated in Figure 67. Since a total resupply system generates a straight line, the breakeven point may be taken as a figure of merit for the space farm.

In order to get a short breakeven time, the mass of material shipped from Earth for the space farm, including biomass, must be kept to a minimum. Because the dominant part of the mass will be the enclosing structure, a design for a low-mass and reusable structure will be discussed. Because structure mass is area dependent, a strong effort will be made to minimize farm area.

Other parameters include an appetizing and high-quality diet, with protein and caloric content equal to that available to affluent people in the United States. Foods not commonly eaten, such as yeast or algae, will not be considered.

Low-Mass Plant Growing Methods. A problem recognized in earlier studies is that of soil mass. Fortunately, plants do not need soil. Successive experiments have shown that many plants will grow

Figure 67 How to Evaluate the Merit of a Space Farm



in sand, vermiculite, styrofoam, or nothing at all, provided they are supported and supplied with nutrients and water. The lowest-mass method the authors found is shown in Figure 68 (Ref. 76).

The plants are supported by styrofoam boards, and a nutrient solution is intermittently sprayed on the roots which hang below the boards. This requires only a small water inventory. A significant advantage of this method is that the roots may be harvested for animal feed. Some grains may require a different method, such as the conveyor belt technique proposed by John Richard Meyers (Ref. 77).

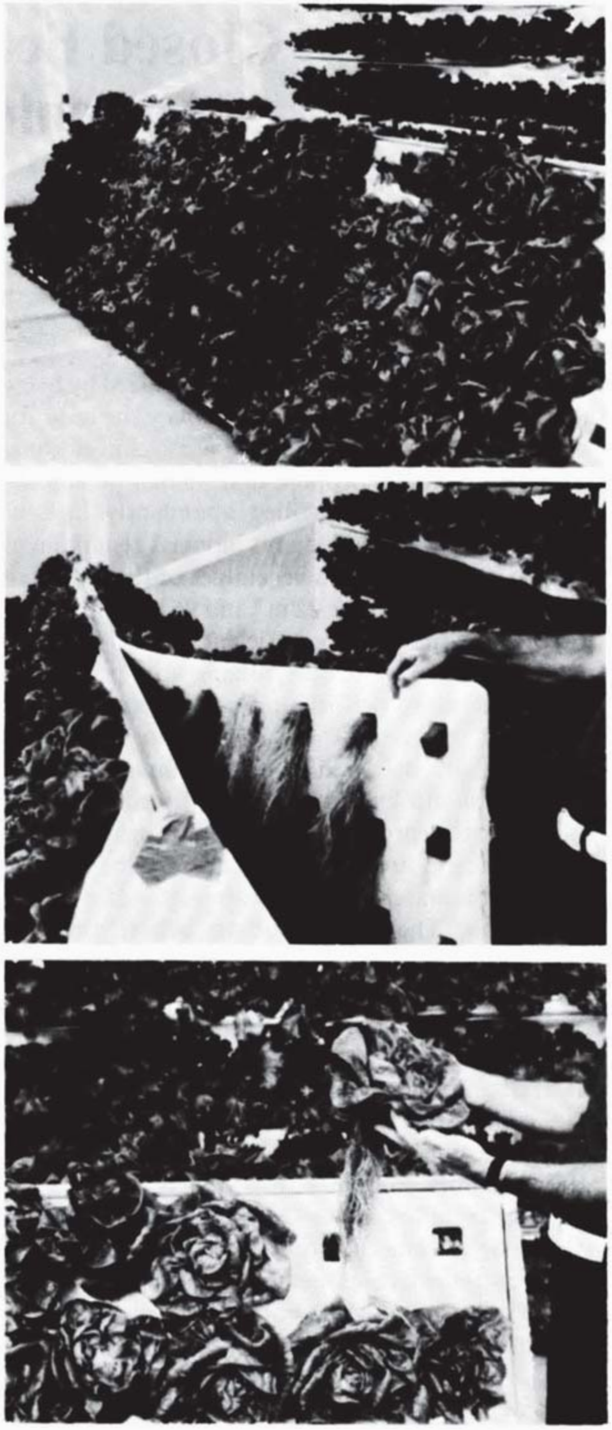
Human Nutritional Requirements. The basic parameters for the space farm are human nutritional requirements. These vary according to individuals, their activities, and culture. Recommended protein allowances per person, for example, range from 45 g/day in India to 85 g/day in East Germany (Ref. 78). Besides protein, people need calories, some unsaturated fats, vitamins and minerals. The amounts needed of these also vary. The conservative approach used here will be to provide a diet in excess of the highest recommended requirements and of familiar food. We will consider the area and mass requirements to grow grain, fruits and vegetables, meat and/or legumes, milk and eggs. Salt requirement problems will be considered in the waste recovery system.

Grain Production. Grain consumption in the United States amounts to some 120 g/person-day direct, and about 2,000 g/person-day indirect (Ref. 79). Much of the indirect grain consumption is inefficiently used to put fat on hogs and cattle. Animal fat, in large quantities, is not necessary in the human diet and may be detrimental to health. The overall food supply design presented here requires 500 g of grain per person-day.

How much area and biomass inventory are required to grow this? Reported dry matter yields range from about 10 g/m^2-day for wheat under average field conditions (Ref. 80) to 1,370 g/m^2-day for hydroponically grown forage under artificial 24-hour lighting, high ventilation and temperature control (Ref. 81). Reference 82 states that *Zea mays* fixed a maximum of 50 g/m^2-day with a 12-hour day under optimum field conditions. In a laboratory experiment, a carbon fixation rate of 30 g/m^2-day (24 hr) was raised to 90 g/m^2-day by optimizing CO_2 levels to 0.13% (Ref. 83).

Provisionally, we will consider attainable a plant

Figure 68 Growing Biomass Without Soil, on Styrofoam



yield of 150 g/m^2-day of dry weight and take a 50% loss due to various inefficiencies. This 75 g/m^2-day figure has been calculated independently by others (Ref. 84). Using ~ 40% harvest ratio (Ref. 85), 16 m^2 should yield the desired 500 g/day of grain.

On Earth there has been no economic incentive for research into growing grains in enclosed optimized conditions. However, the cost of researching this subject would be low as it draws on existing greenhouse technology. Greenhouse yields for non-grains are commonly three times or more field yields per crop (Ref. 86).

The biomass estimates are based on average mass over a harvest cycle. Figure 69 shows various estimated growth curves (Ref. 87); the dotted lines show the average mass.

The estimated average biomass inventory per person for grain production is 70 kg (see Figure 69a).

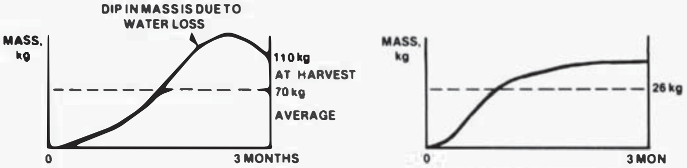
Fruits and Vegetables. Vegetable production under partially optimized conditions on Earth is well-documented. Current commercial yields in a facility in Abu Dhabi, for example (Ref. 88), are:

Tomatoes (High yield)	82 g/m^2-day
Cucumbers (High yield)	89 g/m^2-day
Cabbage	47 g/m^2-day
Radish	50 g/m^2-day
Broccoli (Low yield)	28 g/m^2-day

Without improving these figures, 6 m^2 will produce 500 g/day of tomatoes or other high yield vegetables. We would expect yields of melons to be similar to cabbage on the basis of their similar field productions, and yields of potatoes similar to those of tomatoes, on the same basis (Ref. 89). With unsupported roots, harvesting of potatoes might be automated like the collecting of eggs in a modern egg ranch.

Several improvements over current greenhouse technology may increase yields. A no-matrix culture allows a simple re-spacing of plants as they grow larger in order to use more efficiently the available area. Figure 68, cited earlier, shows how a plant can be "unplugged", or, alternatively, the growing surface can be tilted as the plants grow to change the area of sunlight intercepted. Also, day length, and to a lesser extent temperature, in the Abu Dhabi facility have been optimized. Considering these factors, it seems probable that production could be doubled. For space farm computations, assuming a wide mixture of vegetables with varying yields, we will use an average figure of 125 g/m^2-day (wet mass assuming an average water content of 80%), or, from 6 m^2 area, 750 g/person-day.

Figure 69 Estimated Growth Curves for Various Crops



a. HARVEST CYCLE FOR ONE PERSON'S GRAIN PRODUCTION

b. HARVEST CYCLE FOR ONE PERSON'S VEGETABLE PRODUCTION

c. CATTLE INVENTORY (OF 200 kg HARVESTED, 100 kg IS MEAT).

d. CHICKEN INVENTORY (OF 80 kg HARVESTED, 53 kg. IS MEAT).

e. RABBIT INVENTORY (OF 15 kg HARVESTED, 8 kg IS MEAT).

f. FORAGEINVENTORY

An estimate for the required average biomass inventory (see Figure 69b) is 26 kg per person.

Animal Protein. Is it economically feasible to grow meat in the initial space farm, with mass and area at such a premium? First, as in grain, fruit, and vegetable production, the ideal animal must have high productivity in relation to biomass inventory. For example, only some 20% of the inventory of a herd of cattle can be harvested as meat per year, whereas 500% of rabbit inventory and 500% of chicken inventory (see Figure 69c, d, and e) can be harvested. Second, the productivity per unit area of animal protein must approach that of humanly usable vegetable proteins.

Because of their high reproductive rates and feed conversion ratios, chickens and hogs have often been suggested as the most efficient producers of animal protein for use in space. However, for efficient protein production, hogs and chickens require a diet also suitable for human consumption (Ref. 90), and the conversion loss is large. It is true that hogs in China are fed materials inedible to people, such as sweet potato vines and rice hulls, as part of their diet (Ref. 91). The remainder of the diet is composed of the same foods that people could eat and thus is still in competition with people. Their meat productivity on such a diet is quite low (Ref. 91). High-efficiency chicken production is based on animal protein from fish meal and animal butchering waste, soybeans, and grain. Again, because of competition with human diet, these animals will not be considered as major sources of protein for the construction site space farm.

Dr. Kenneth Olson, of the University of Arizona, has proposed the raising of alfalfa or other forage in a greenhouse environment for rabbit feed (Ref. 92). Alfalfa (a legume) produces high yields of balanced protein but is not a suitable protein source for people because of the fibrous content. With the addition of a little salt, alfalfa has been shown to be acceptable as a complete rabbit feed (Ref. 93). For reasons of palatability and yield losses, we will not consider extracting the alfalfa protein directly for human use.

One square meter will house a doe rabbit and her litters. The young are butchered every two months just before the next litter arrives. The productivity of this unit is approximately 143 g of low-fat and boneless meat per day. Feed requirement is on the average of 700 g/day dry mass (Ref. 94), requiring about a 10 m^2 area at 70 g/m^2-day. Using a multiplying factor of 4 between dry feed and live forage, the farm must produce 39 kg of forage every two weeks. Biomass inventory of forage would be about 30 kg. Biomass inventory for the rabbits and forage together would be 40 kg (see Figure 69 e, f).

In terms of protein production per m^2 per day, we estimate rabbits would produce 4 g, grain 4 g, and soybeans 6 g. It should be noted that rabbit meat can be cured like ham, and made into sausage and liverwurst; it is a mild-flavored meat that can be cooked many ways, even as rabbit-burgers.

This farm system generates food for two additional kinds of animal protein products at no additional cost in photosynthetic area. Ruminants can convert the waste materials, e.g., stems, leaves, and roots, from vegetable production into milk. Tomato vines, for example, are about 15%-24% protein, and, raised under greenhouse conditions, they can be fed to ruminants (Ref. 95). Cucumber vines, cabbage leaves, and melon vines are also valuable feeds. A reasonable figure for the mass of vegetable and fruit wastes is 300 g/day dry mass per person. Assuming that most of the vegetables have high forage value, e.g., stems, roots and leaves of species such as tomatoes and cabbage, a ruminant could utilize an equal mass of low forage value material such as straw, sorghum stalks, etc., from grain production.

At this point, a comparison should be made between the two commonest domestic milk-producing ruminants (Ref. 96):

	Goat	Cow
Mass	56 kg	540 kg
Dry feed intake/day	2 kg	16 kg
Milk produced/day	5 kg	20 kg
Milk/feed	2.6	1.25

In summary, a goat will produce more than twice as much milk for a given amount of feed as a cow.

For an optimum utilization of these forages, goats, as well as cows, require some grain. The 500 g/person-day grain allowance contains 60 g of protein. This may be eaten directly or half of it (30 g protein) diverted as goat feed, for a total dry mass, including forage, of 850 g. This will return 2 kg of milk containing 64 g of protein with a better amino acid balance and higher mineral and vitamin content than the grain used as feed. Also, our space farm can now produce ice cream.

This system provides one goat for every 2.4 people, or a thousand goats for the proposed space farm.

For those who cannot digest the lactose in milk, or just for variety, cheese can be made with only a slight loss in food value. As for the culinary

Table 23. Proposed Diet (Per Person)

Crop	Area	Biomass	Food Mass/ Day	Protein
Grain	16 m^2	70 kg	250 g	30 g
Fruits and vegetables	6 m^2	26 kg	750 g	10 g
Meat	11 m^2	40 kg	143 g	40 g
Milk	5 m^2	20 kg	2,500 g	64 g
Eggs	.5 m^2	1.5 kg	15 g	5 g
Total	32 m^2* 6 m^2**	165.5 kg	3,658 g	149 g

*Photosynthetic
**Non-photosynthetic

qualities of goat's milk, under conditions of proper feeding and sanitation, the flavor is as acceptable as that of cow's milk. Cream and butter can also be separated from goat's milk. Billygoats have a justifiably bad reputation in regard to their odor; however, artificial insemination for goats is a well-developed technology and eliminates the need for billies on the space farm.

The added biomass would be about 20 kg per person; added non-photosynthetic area would be 5 m^2.

Chickens can make eggs from leftovers on plates, kitchen waste, and butchering waste. These foods also have traditionally been fed to hogs as well as to chickens. Egg production is a more efficient food converter than pork and lard production. Three or four eggs per person per week could be generated with an addition of 1.5 kg of biomass and 0.5 m^2 of non-photosynthetic space. Aside from their nutritional value, eggs allow people to make cakes, waffles, omelets, mayonnaise, and many of the other amenities of life.

Table 23 summarizes the major components of the proposed diet per person.

Assuming low-calorie vegetables, such as radishes and cabbage, this diet contains 3,000 C. For a more active construction worker, a substitution of potatoes for most of the vegetables and soybeans for rabbit meat would raise the caloric intake to about 4,300 C.

The experimental evidence mentioned above regarding possible rates at which plants can grow dry matter is of special interest. If grain and forage production can be maintained at a rate of 150 g/m^2-day, given optimum CO_2 concentrations, light, temperature, humidity, and nutrients, the space farm could be cut down to a photosynthetic area of 19 m^2 per person. This subject is certainly worth further investigation.

Stability. A great deal of concern has been expressed about the "stability" of the space farm. We will define stability as the capacity of the space farm to continuously provide adequate food and air. Concern about this subject is certainly justified, as farm yields on Earth are highly variable from year to year and occasionally fail entirely. There are reasons to believe that the yield of a space farm will be more stable than that of an Earth farm.

It is instructive to look at the causes of yield variation on Earth and see which will apply to a space farm. Major causes are: weather, weeds, insects, rodents, and disease. Weather simply does not apply in space, assuming that engineers can solve the problems of temperature control.

The initial seeds for the space farm could be individually inspected to keep out weeds. If a few weed seeds did get through, the space farm area is small enough so that they would be spotted and removed. Simple fumigation of shipments from Earth should eliminate the insect problems. If an undesirable insect did get in, the procedures discussed regarding disease in this paper would deal with the problem. Alternately, low toxicity insecticides, of which pyrethrum and rotenone are examples, could be used. Rodents are even easier to keep out than insects, and we would not consider the problem further but for the fact that scientists will inevitably bring white mice and rats. In the event some escape, a cat may be necessary.

Disease organisms will be much harder to keep out or control, and will likely be brought in with each new shipment from Earth. The space farm environment is a rich one, and nature seems to have available organisms able to inhabit even the poorest of man-made environments – for example, jet fuel. The environment of a space farm is, in essence, that of a greenhouse on Earth. Molds and viruses have been troublesome in greenhouses, but a variety of control methods have been developed. Some of these, fumigation with methyl bromide for example, will not be acceptable in space. Other methods, such as steam sterilization, might be satisfactory. A number of horticulturists should be consulted on greenhouse disease problems and methods for their control. Mold problems are particularly troublesome in the high humidity conditions sometimes used in greenhouses. In space, the humidity may be made as low as desired by selecting the capacity of the water condensing system. For grain crops, moderately low humidity would be essential. In any case, the science of coping with micro-organism competitors and pathogens has a long history of development dating back to the time of Pasteur. The space farm would certainly stock vaccines, antibiotics, and medications. It should also be noted that bacterial and virus diseases usually attack a narrow range of hosts, sometimes even a single species or genotype. The stability of a space farm in relation to disease attack would be enhanced by growing a wide variety of crops and animals.

In many natural ecosystems, the biomass of various species varies widely over time. The most commonly cited example is that of the rabbit and rodent populations of the far North. Natural systems have feedback loops which cause oscillation. A farm differs from a natural system in many ways, the most important of which is human control of the size and composition of the plant and animal components. This precludes oscillation, if the farmers are competent. The space farmers would plant a proper mix of crops for the anticipated needs, breed a correct number of rabbits to eat the forage planted for them, watch the system carefully, and take corrective measures when necessary in much the same way as is done on Earth.

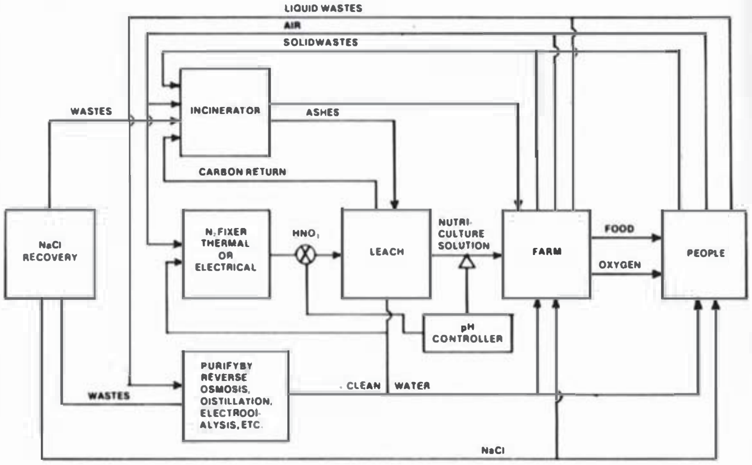
Nevertheless, for those readers convinced of the general perversity of things (Murphy's Law), a number of fall-back positions are available. For one thing, the diet proposed is excessive; a substantial fraction of the crops could be lost and no one would go hungry. Also, there is a large safety margin in terms of stored food and seeds, food in process (cheese being aged), and standing meat inventory.

Let us assume a disaster, nature unspecified, that kills every plant on the farm but leaves the people and animals unaffected. What would be done in this case, which is similar to an Earth crop failure, would be to butcher all of the animals that stored or salvaged food would not feed for the next two weeks, and freeze or dry the meat. After cleaning up the mess, the farmers would plant the fastest growing seeds available.

The CO_2 content of the air would not reach a problem level for at least two weeks, even if nothing were growing. With planting, in one week the CO_2 level would be on its way back down. In two weeks, the forage production for rabbits would be back to normal, and in three months, the entire farm would be at normal production level. The two weeks of leeway before the CO_2 levels become uncomfortable would allow the ultimate fall-back position, help from Earth, to arrive.

Waste Product Recycling. There is only a small provision in the biomass calculations for inactive material. To maintain the high levels of CO_2 required for rapid plant growth and to supply the plants with minerals, the solid waste products from people, animals, and plants must be recycled rapidly. Incineration seems to be the fastest method to return material. Liquid wastes would be combined with the basic pH ashes and the acidic output of the nitrogen-fixing subsystem. Problems of solubility, mentioned in early NASA studies (Ref. 97), probably stem from the low solubility of calcium and phosphorous compounds in basic solution. The solution formed of nitric acid and ashes makes an excellent pH-controlled nutrient solution for the plants. In a closed system, with no traps, the solid waste material will have all elements which the plants require except nitrates. An initial supply of salts will be necessary, but most of them would be supplied by the food initially brought from Earth. Figure 70 shows the flows in the waste recovery system. A problem may exist because nitrogen-fixing methods, both thermal and electrical, form nitrites as well as nitrates. Nitrites are somewhat toxic to plants.

Figure 70 Waste Reclamation System



A burner system serves another function – the maintenance of air purity. A large variety of unpleasant substances (hydrogen, carbon monoxide, hydrogen sulfide, ammonia, aldehydes, ketones, hydrocarbons, etc.) are formed as metabolic byproducts or come from sources such as cooking. The technology for coping with these substances has been intensively developed over the last twenty years in connection with nuclear submarines. Some of this information is classified; the rest is available in NRL reports and BuMed reports.

The U.S. Navy has accumulated at least 22,000 man-years of experience in closed environments (Ref. 98). This has taught them to bring nothing into a submarine which is harmful after passing through a catalytic burner. Mercury and fluorinated or chlorinated hydrocarbons are examples of substances that must be excluded. Much of the data on submarines derived from U.S. Navy experiments in connection with sociological, psychological, and medical effects of closed environments will be directly applicable to space habitats.

At some point in the cycle, salt (NaCl) must be recovered, as it is used extensively in the intake of human food. Soap may prove to be another troublesome item to recycle. Although it is useful and easy to make from fat and ashes in the space farm, water containing it may have to be distilled if the concentration is detrimental to plants.

An Early Space Farm. The construction site facilities will be used until Model 1 is finished, a matter of some years, as a substantial industrial base must be set up to build Model 1. Even at only one-half kg per person per day, five years of supplies for 2,400 people will weigh 2×10^6 kg. Is it economical to lift enough material from Earth to make a space farm? The authors believe this to be possible, especially if most of the mass of the space farm is made of elements which must be imported from Earth for Model 1 anyway.

Using this concept, a "first pass" design for an enclosure for the space farm has been developed. The authors are not particularly skilled in this work, and before others quote the conclusions, the concepts and numbers should be verified, the cosmic ray shielding problem solved, and the design and assembly techniques for the space farm should be put forth in detail.

The dominant design factors influencing the mass of the space farm enclosure are the photosynthetic area and light levels required. For steady state conditions, the light input to the farm must be equal to the black-body radiation from it. At a temperature of 300°K and an emissivity of 0.9, each m^2 will radiate 410 watts. Maximum sunlight intensity on Earth is over twice this value, but 410 W/m^2 will require that the wall be about the same as the photosynthetic area. Active cooling would allow tiering of plant growing areas, as waste heat could be radiated at 1,300 W/m^2 if the temperature were raised to 400°K. On the assumption that passive systems are more reliable, a single level of photosynthetic area is proposed. Animal pens and work areas may be placed under the crop areas.

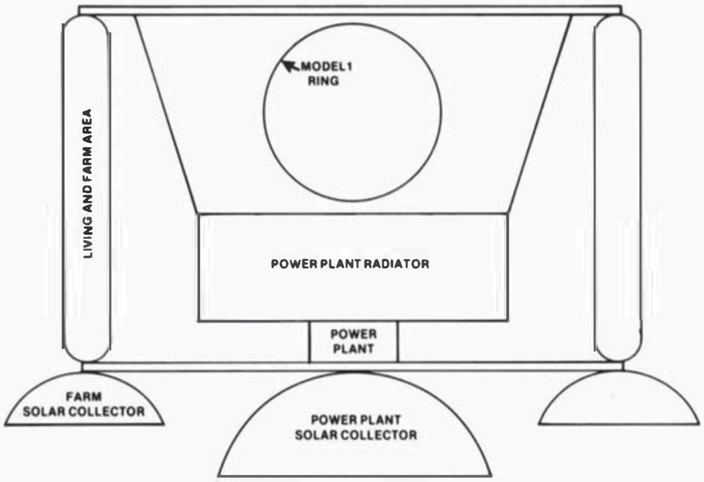
At 32 m^2 per person, the photosynthetic area requirement for 2,400 people is almost 8 hectares (80,000 m^2). An additional 20,000 m^2 will be allowed for walkways and other uses. Besides a 100,000 m^2 area, other parameters are as follows: Geometry is similar to Model 1, except for a crop-illuminating optical system which does not use cylinder area for windows. No components will be used that are larger than 15 m in diameter or heavier than a space shuttle load. An internal air pressure of 2/3 atm (10 lb/in^2) will be maintained. The main structural material proposed--carbon phenolic composite – while a fairly new material, is used today for golf club handles. It costs about $84 per kg, but the price is coming down and, compared with lift costs to L5, is low enough. Its main advantage is that its elements are reusable later for the biomass of Model 1. Characteristics are: tensile limit, 100,000 lb/in^2; density, 1.4. It could be fabricated on Earth as hoops 45 m (147 ft) in diameter, and triple-looped (like a band saw blade) to 15 m for shipment to L5. An area of 50,000 m^2 per cylinder requires a length, not counting the end caps, of 354 m (1,160 ft). The end caps would be used for human habitation, as has been proposed for Model 1.

Simple calculations indicate a thickness of 9 mm (.354 inches) would carry the hoop stress, and 2.2mm (.088 in) would carry the end cap loads with a 100% safety factor. The longerons would be rolled up for shipment and the ends looped over and attached to end rings at L5. If some 1.5 mm (.060 in) of plastic were used to seal the air inside the cylinders, the total wall thickness would be 1.25 cm (1/2 in). Diffusion rates through the wall will have to be considered. The area, including end caps for one cylinder, is 56,000 m^2 (610,000 ft^2), or 680m^3 (24,000 ft^3) of material. The enclosure would therefore weigh $.97 \times 10^6$ kg per cylinder. The volume enclosed by each cylinder is about 0.6×10^6 m^3. Using an air density corresponding to 2/3 atm, the air inside will weigh 0.53×10^6 kg. Therefore, the mass of two cylinders for air and enclosures would be 3×10^6 kg.

The crop-illuminating optical system envisioned here concentrates sunlight into a beam that enters through a 15 m diameter glass window at one end of each cylinder. The beam is spread out by light scatterers down the cylinder axis. Assuming filters and losses reduce the effective solar radiation to 800 watts/m^2, the concentrator area outside the cylinder required for each one (see Fig. 71) will be 25,000 m^2, or 180 m in diameter. The power level in the beam, although high, is well within the limits for glass.

Figure 71 shows the assembly of farm cylinders and light concentrators. For scale, a 33%-efficient 40 MW power plant and a Model 1 ring are shown. At 10kg/kW, the power plant would weigh 0.4×10^6 kg.

Figure 71 Construction Site Facilities, Including Farm



A low mass for much of the farm structure – plant supports, animal cages, plumbing supports, etc., and some of the optics – might be achieved by using wires or cables across the cylinder axis to build the structures in tension.

Including these structures, an estimate for the mass of the farm equipment, optics, windows, compression struts, pumps, fans, burners, pipes, ice cream makers, etc., is needed. Provisionally, the mass is estimated to be 0.9×10^6 kg. With the addition of the air and enclosure mass of 3×10^6 kg derived above, this results in a farm and living space total mass of 3.9×10^6 kg. The biomass, including people at 100 kg each, would weigh 0.73×10^6 kg, for a total of 4.6×10^6 kg and an enclosure to biomass ratio of 5.4:1. It should be noted that even if the space farm were not included in the construction site facilities, a substantial fraction of this mass would still be required for living quarters. Also, the morale of the construction workers on a diet of dehydrated and reconstituted food might leave something to be desired.

Human Lab Requirements for the Space Farm. Highly mechanized farming in the United States is full-time work for about 5% of the population. This may be a reasonable estimate for the space farm as well. While the level of mechanization will be lower, the lack of weeds and insects should compensate for this.

This farm proposal includes a lot of goats. Feeding and milking by hand will require 4 or 5 minutes per day per goat. At this rate, 10 to 14 people would be required. The meat supply will require butchering about 350 rabbits per day. At 10 minutes per rabbit, 8 people could do the work. Both of the above time figures come from the personal experience of the authors.

Some, perhaps most, of the farm labor may come from volunteers working after regular hours. A large number of people like to raise animals and consider it recreation. An even larger number of people garden for fun. The space farm would be a gardener's paradise and would doubtless contain a few ornamental flowers from smuggled seeds.

One job the authors consider too tedious to attract volunteers is the hand-pollenization of vegetables. For pollinizing vegetables, several hives of docile bees should be included to complete the farm for a "land of milk and honey" (Ref. 99).

Acknowledgments

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DISCUSSION

Q. *You intend to increase the carbon dioxide and the amount of sunlight. Have you worked out what that would do to the heat balance of the colony?*

A. No. The heat sink problem has not been tested. The carbon dioxide should have virtually no effect on the heat balance in a space environment. It might on Earth, but even that's questionable.

Q. *The government recommends about twelve different nutrients and other items in the recommended daily requirements for adults, of which you discussed calories and proteins. I was wondering if in your program you considered other things like riboflavin, niacin, calcium, ascorbic acid, vitamins, and so on?*

A. There will be no problem with nutrients in the diet we propose. We are not talking about eating amino acids, pure carbohydrates or other artificial foods. Two pounds of vegetables a day, for example, have enormous nutrient value. How many people eat two pounds of lettuce and tomatoes a day? Of course you can increase that; e.g., spinach, chard, and other vegetables are quite favorable to grow. So to make available huge amounts of vitamins and minerals is no problem, assuming you recycle properly. As long as you are not heaping up a stack of garbage that isn't being recycled, you will keep the nutrients and the various trace minerals.

Q. *Did you assume twenty-four hour sunlight for the plants?*

A. No. I was assuming just the greenhouse productivity we get on Earth. But I would assume that we *would* grow for 24 hours in space.

Q. *We could certainly do that. But will the plants react normally and produce three times as much as they do on Earth?*

A. Not all plants. For instance, tomatoes take a complex of length of day and temperature to set fruit, but grains, for example, can grow very well under twenty-four-hour-a-day sunlight. It varies a lot, so we would have to make a choice of crops on the basis of what produces the best. A lot of research will be needed.

Q. *What do you do with dead peoples' bodies?*

A. I think we would have to obtain a release to allow them to be recycled along with everything else. I personally find that not at all unacceptable; in fact, I myself would much prefer it that way.

Q. *You said there would be 2 kg of inventory for every pound of person. I don't know what reasoning you used to get that number, but Earth for the last two centuries has been operating on a philosophy that there is all that biomass out there and we'll never make a dent in it. Now that philosophy is changing, and we want to treat the biomass with respect. But you would still need a reasonable buffer against catastrophe and inefficiencies. You might want to make that reserve ten times as great, so that things could go wrong and you could still get a product.*

A. You would have a problem with the huge masses just growing there. What do you do with it? Do you just chop it down and compost it without eating it? That's a problem. If you wanted a buffer supply of food, say two months, you wouldn't want to have a monster biomass standing to achieve it. You could simply store freezable food for that period; in two months you'd be back in full production. Remember, we're not talking about a monoculture, like a bunch of chlorella. We have a diverse system; enough to be biologically stable – at least twenty or thirty different species. If, for example, all your animals died off, there would still be sufficient plant protein, according to the World Health Organization, to keep you from getting in bad trouble. You would change from optimum to minimal, but still adequate.

Q. *But if the entire world food crop died tomorrow, theoretically, everything would go with it. I think you are just as vulnerable.*

A. But in this habitat, if the wheat crop goes, two months later the new wheat crop is coming in again. It's a very short cycle.

Q. *But the rabbits haven't died with the wheat.*

A. You cut the population of your rabbits. You just butcher all the rabbits and don't breed them for two months, and then you start right up again with the remaining biomass.

Q. *My question also has to do with the stability of the system. Odum in Atlanta, as far as I know, operates the only closed, ecological system in the world, and the largest animal in it is a water flea. I think we ought to pay attention to the problem he points out: that stability requires diversification. He suggests that such diversification is necessary, that less than five percent, more like two percent, of the total biomass be available to humans. How does that compare with your system assumptions?*

A. Odum's is a stable *Earth* system. His figures are reasonable, and, I believe, testable. Will it turn out to be like an arctic biosystem, where there are fantastic fluctuations in the food, or like a tropical system, which has incredibly complex varieties of species, and the amount of food available in a square mile remains very constant as compared to fluctuations in the arctic environment? But in space, the environment is very stable. The sunlight is always coming in, you're maintaining it at the same temperature, and so on. We would really be simulating a tropical environment, only better.

Q. *There's no possibility for disease?*

A. Right. And there is no source for the diseases. Should a disease be shipped in inadvertently, it's going to kill maybe the rabbits, or maybe the goats, or maybe the wheat, but it's unlikely that you'll get one disease that will wipe out all three of them.

Q. *I have a question about the esthetics. The bill of fare that you are proposing is certainly more appealing than distilled urine and chloraldehyde, but rabbit and spinach just wouldn't appeal to me night after night. What about the possibility for artifical flavorings and texturings which would give at least a fair verisimilitude of clam chowder, shrimp, roast beef, steak, among other things?*

A. Some of those things are doable and some are not. You could probably manage the flavoring all right, but the actual growing of simulated steak has not been successful. However, growing shrimp and other seafood, if you have the water to do it, turns out to be very favorable.

This brings up a good point: can we get water locally, rather than from the Earth? Commercially on Earth, aquaculture can produce as much as ten thousand pounds per acre per year; that's a system that uses four species of carp. I was told that if you include fresh-water shrimp and clams and a few telopia to fill in the extra niches, you could get up to twenty thousand pounds per acre per year. The water mass is probably too much to make it worth importing the water from the Earth, though, so a local supply would be needed.

Q. *Because the cost of the farming installation is very sensitive to total atmospheric pressure, could you reduce it below 10 psi? Also, NASA has estimated the resupply of the people in the construction system to be equivalent to 8,000 kilograms per person in 5 years. That is approximately forty times as much as the biomass which you have in your inventory. That means that you can afford to go up by a factor of ten in your biomass inventory and still save a factor of four over the NASA resupply estimates.*

A. The atmospheric question is a good one. NASA uses seventy percent nitrogen to minimize chances of fire; once burned, twice careful. That *is* a real problem. But I would very much like to see the fire capacity computed on the basis of a quarter g, which I think is plenty adequate to orient plants, and the partial pressure of oxygen the same as we have on Earth, but with perhaps only five or ten percent nitrogen. There is no real reason why the farming area has to operate in the same atmosphere that you have in the living habitat.

Q. *Do you have any fear about genetic drift? Perhaps from cosmic-ray damage?*

A. In ordinary breeding, just from the fact that you have so many genes, any animal breeder can tell you that it is a constant battle to keep your animals from degenerating, because of the noise that enters into the system. So, I think genetic drift wouldn't be any worse than the natural tendencies on Earth.

Q. *But that's the point. This is basically a closed system. You've probably got the worst possible conditions as far as cosmic rays are concerned.*

A. There have been some experiments involving this. They put an unshielded nuclear reactor out in the middle of a forest, and it really cleaned house on various kinds of plants, but not on others. There is a lot of variation in the ability of plants to tolerate radiation. You could probably manage to pick plants that could stand more radiation and still be edible, but at the low radiation levels that people would worry about, plants are simply not affected. I believe the experiments showed hardly any effects at all below the ten roentgen per day level. I don't believe space radiation, even in a solar flare, would provide much more than that.

Q. *I see the possibilities for bourbon, but I'm worried about the beaujolais. You touched briefly on the question of fruits; is there any possibility of forcing grapes?*

A. Very likely, but grapes do require special treatment. Your wine after a few generations would probably be a little different than it was initially, but who knows? Perhaps it might improve!