Limits of Remote Ecosystems Containing Man

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A vigorous defense of a nonmechanized ecosystem as the most efficient closed system is made by the author, a famous ecologist. His work has been aided by a grant from the NSF on ecological microcosms, NSF G13160. His present address is the Puerto Rico Nuclear Center, Rio Piedras, Puerto Rico.

Summary

Considering a controversy among those attempting to provide support for man in space, three kinds of systems are contrasted: A. the conventional engineering approach with pipes, electrical circuits, fuel, and maintenance parts sent from earth; B. the physiological approach with a few biological species in culture to complement man in a simple ecosystem, which also requires heavy subsidies in energy materials, controls, and parts from earth; C. the ecological approach with a complex multispecies climax ecosystem self sufficient with all its maintenance and control functions in the form of many highly miniaturized and specialized biogeochemical circuits.

Some fallacies in previous estimates of the amount of solar energy required to support man in space are described: A. the incorrect use of theoretical reversible high efficiencies for computing potentials in defiance of the great body of empirical data on the moderately low efficiency of successful self maintaining ecosystems; B. the omission of the energetic costs of the accompanying species necessary for stable chemical cycles and system maintenance; C. the neglect of the high trophic position of man and the necessity of heat losses during food chain transfers to him. The estimated minimum solar area for a closed and stable climax ecosystem supporting man without outside subsidies is estimated as 2 acres. To develop such a system including man for space encapsulation, the multiple seeding method is recommended.

A Controversy

In the schoolrooms of America experiments with closed ecological systems (ecosystems) have been a regular feature of science teaching for many years. The closed aquaria and terraria have served well to illustrate the interdependence of the parts of nature and the ability of biological components to become sufficiently organized to maintain a system of viable chemical cycles. There have been thousands of examples with imaginative adaptations to local conditions producing tremendous variety. Unfortunately these exploratory experiments have not been followed by the usual scientific procedures of replication, measurement, and published report so that the experience has not been generally cumulative.

Now the space effort of the nation has a desperate need for the knowledge of closed escosystems. For lack of knowledge of overall potentials and capabilities, a controversy is now developing that may drastically affect planning for the billion dollar space program. How many million dollars have been wasted by the national government because of a blind spot may become more and more evident as delays in getting a sustained system for man in space accumulate.

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The issue is a controversy between three corners whose different approaches are described as follows:

A. Man in space can be supported as part of an *ecosystem predominated by chemical engineering apparatus* whose fuel and means of parts replacement is supplied from earth just as in any industrial enterprise of conventional type. Oxygen, carbon dioxide, waste, and foods are to be handled mainly with nonbiological processes. Such a system is dominated by pipes and electrical control circuits. This conventional engineering approach has been instinctive with the engineering and physical science personnel in the National Aeronautical and Space Administration (NASA).

B. Man in space can be supported by an *ecosystem predominated by a few biological species* present under culture-like conditions. Such a plan is illustrated by efforts with algae or duckweed of one species coupled in a small closed system with a mammal. Energy in such systems is partly solar and partly from conventional fuel used in the long sequence of events involved in providing pipes and electrical controls with maintenance from earth. The simple biological system has been supported in biological divisions of NASA under influence of physiologists and microbiologists.

C. Man in space can be supported by a *climax (steady state) ecosystem of many species* including a sufficient number of compatible and specialized types so that the normal structure of living components develops (logarithmic pattern) and so that stability is self-contained in the many biogeochemical pathways. Systems of the complex multi-species type are the ones so abundantly studied in ecosystem science and successfully operational under closed conditions. Although it is the only system already found self sufficient in nature it has not been adequately represented in the space program, possibly for lack of adequate communication and spokesmen. The issue may not be defined at an administrative level high enough to bypass the roadblock of committed specialists in other fields.

When a committee of the National Academy of Science was set up entitled "closed ecosystems," no member of that committee professed to be in ecology, the science of ecosystems. Consequently projects for studying the parts of normal ecosystems in simplified culture systems, the fields of algology, microbiology, physiology, and agronomy were fostered, but the study of the organization of whole complex systems and their adaptation to capsules was generally omitted. Then when the simple systems showed inherent instability and high outside energy costs for control which might have been predicted from general ecosystem theory based on population studies and arctic data, physical scientists lost confidence in biological components so that the climax ecosystem approach was shoved further into the background without a hearing or trial. Charity requires the statement that this is another example of a recurring and difficult problem of our times frequently discussed by leaders in scientific administration, the situation when specialists in field A inadvertently select a panel of scientists from field B to pass on projects in field C.

In the paragraphs that follow the present author uses some general considerations of ecosystems to compare the complex climax system showing both its advantages and its size disadvantages.

An Introduction to Ecosystems Pertinent to Space

Like the pigmy in the equatorial rain forest, primitive man evolved along with natural ecosystems of which he was a very small part. His metabolism was a minor part of the total energy flux and his wastes a small part of the biogeochemical cycles of material. When later man was part of the industrial ecosystems with a large part of the power and material fluxes in his cultural control, his special fossil and atomic fuel sources exceeded those from the sun, but much of the total fuel consumption necessary to run the system was over and beyond that food to be consumed in human metabolism. Man was metabolically still a small part of his ecosystem.

Both the primitive and the advanced systems are special cases of the general ecosystem subject to the laws and limits applicable to such systems generally. The energetics and biogeochemical cycles as related to component populations are a much studied central problem in ecology with a vast literature.

In this symposium we are directed toward the construction of remote, closed, or semi-independent ecosystems containing man and the possibilities per unit of available power supply. Since systems with independent self reproduction and maintenance are not within the experience of most conventional engineering, it may be profitable to examine some principles of ecological engineering. Since it is believed that millions of years of organic evolution have been guided towards development of complexes with maximum useful power output for survival and maintenance, an examination of maximum performances in known self-reproducing and self-maintaining ecosystems may provide thermodynamic guides for further ecological engineering involving closed space systems containing man.

First consider some definitions, general aspects of ecosystems and several special types pertinent to this symposium.

Some Ecosystem Types Classified by Flux Specifications

In Figs. 1 and 2 are set out boundaries by definition that may be applied to natural or engineered systems so that the fluxes across the boundaries are functional specifications and the processes within the boundary are system functions. Fig. 1A indicates some principal system processes, gross photosynthesis (P) and its reverse process total system respiration (R). At the top are fluxes in and out of organic matter; at the bottom are fluxes in and out of inorganic raw materials. M is the rate of maintenance of structure by replacement of parts balancing the inherent dissipative tendencies. P, R, and M are measured in $gm/m^2/day$ of carbon or oxygen or similar units.

Just as the kinds of ecosystems are grouped according to their material flux specifications, so ecosystems may also be classified according to their power supplies some of which are indicated for the general case in Fig. 2. The energy diagram illustrates both the conservation of energy of the first law of thermodynamics and the transfer of free energy flux into irreversible heat flux as required by the second law. It also indicates the auxiliary types of energy provided ecosystems from such often overlooked sources as stirring by waves in nature or stirring by apparatus in the laboratory. Quantitative energy flow diagrams have been proposed in rough outline for about two dozen kinds of ecosystems on earth, including such diverse types as salt marshes, herb fields, tundra, and parts of the Black Sea. Some operate on solar energy alone; some on organic fuels; and some have heavy supplemental use of mechanical and heat energies as in the transpiration of forest leaves or the metabolic adaptations of stream animals to water flows.

When boundary conditions are set for an ecosystem, the initial state passes through various transient states that are termed succession, involving the accumulation of necessary structure, species, genes developed from past evolution, raw materials, and controls. Eventually a steady state develops and is termed a climax. Such a climax has a great diversity of types, many mechanisms of adaptation among its functional units, mechanisms for maintaining stability, mechanisms for controlling competition and reproduction, and systems for self maintenance. As the system which survives, the climax is making the best use of available power for useful purposes towards competitive existence in comparison to other systems of alternative composition. Studies of those climax systems that have long histories of permanence indicate some similar diversities, efficiencies, and structural properties as set out in Table 1. As independently determined by those working on terrestrial systems, stream systems, chemostats, and algal steady states, a climax can be achieved for any set of specified fluxes which permit the maintenance of adequate internal structure. Famous climaxes are the tropical coral reefs, the equatorial rain forest, the arctic tundra, the fire-climax pine forest, and some deep lake systems. The various kinds of ecosystems may have P and R in various ratios in succession and in climax, depending on the combinations of fluxes in the boundary specifications. Although this is not the place to summarize all of the combinations, nor to present various possible examples of ponds, forests, chemostats, turbidistats, pollutions systems, or marine gyrals, we can set out some special systems of interest in this symposium as diagrammed in Fig. 1.

First, in Fig. 1B, a rudimentary system of

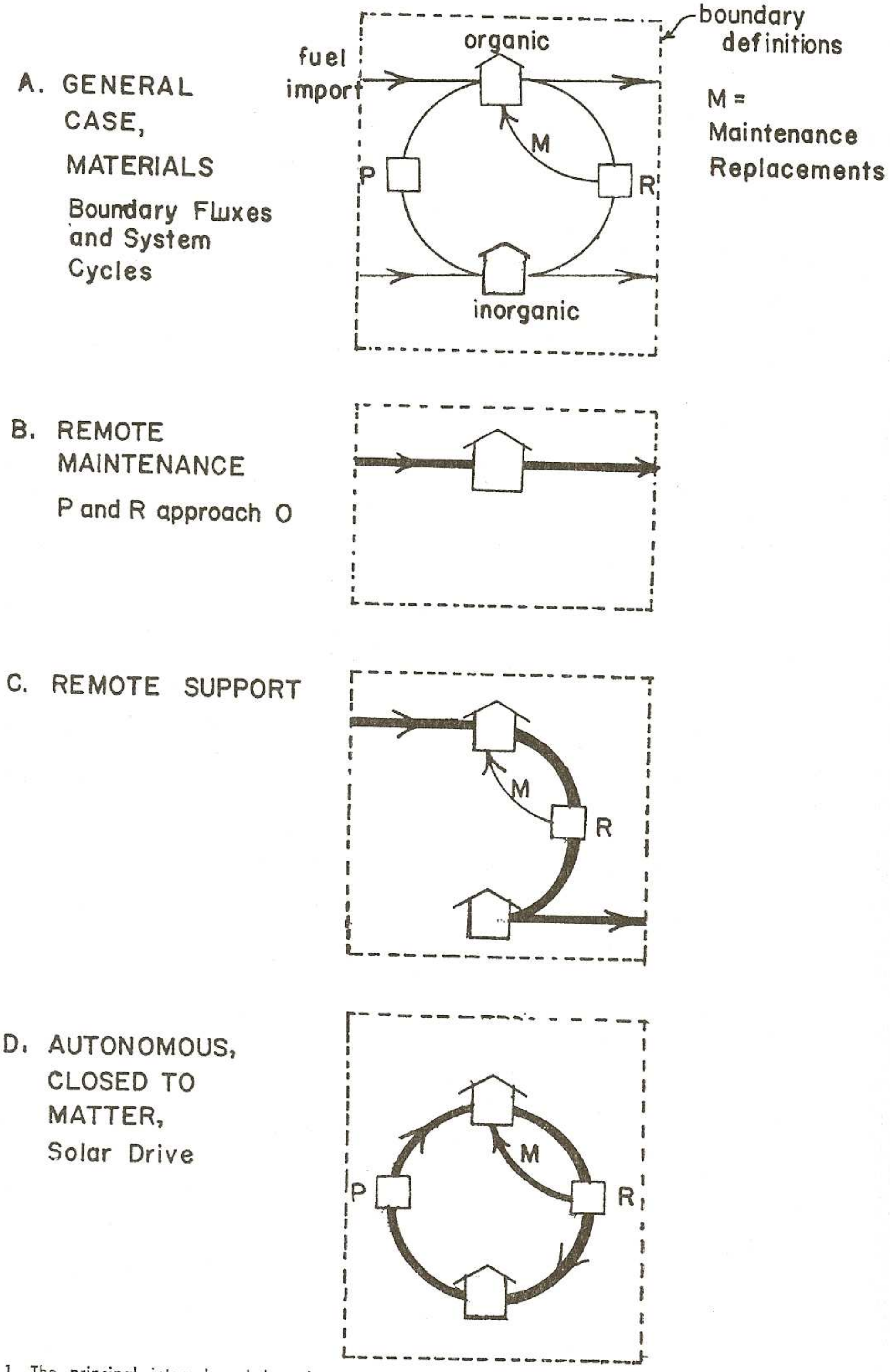

Figure 1. The principal internal and boundary processes in 4 classes of ecosystems. P, gross photosynthesis; R, total system respiration; house boxes represent storages.

remote maintenance involves the import of preformed parts substituting for a synthetic replacement process within the system. The ultimate theoretical case of this type involves no respiration, maintenance, or self reproduction in the remote location, but merely import of preformed equipment and discard of worn equipment (biological or nonbiological). Such systems are not living in the usual sense of including a whole organism. No fuel expenditure is made within the system. Apparently, this type is rare without much precedence among ecosystems competing on earth. One might consider the transport of nonmetabolic spores as life in steady state in the upper atmosphere as a far fetched illustration. Man's probes in space have mainly been in this class without system maintenance. Their survival time is short like those of earth ecosystems without maintenance.

Second, in Fig. 1C is the system of remote power and material support with common precedence among the ecosystems on earth where organic matter as fuel, food, and temporarily-living parts are imported. Stream riffles in shady river deltas, pipe growth systems, oyster reefs, piling fouling systems, and trickling filters are examples. Because of the energy supplied from outside both in organic form and as circulatory energy for transport of gases and removal of wastes, such systems are highly competitive with those nearby running on solar energy alone. In those present satellite systems which include man, there is already a substantial human maintenance respiration supported by remote fuel supply as in the type diagrammed in Fig. 1C. However, since such systems do not provide total system maintenance, but run on storage and depreciation allowances, they are not as yet climax ecosystems.

As long as low temperature atomic power depends on an industrial complex that runs on fossil fuel energy, it must be classed as part of the remote support system as an effective energy transmission device with high power to weight ratio.

Third, in Fig. 1D is the system with materials closed so that all matter is recycled with complementary ratios of elements in photosynthetic processing as coupled with respiratory recycling. Power is entirely derived from the sun. Systems of this class were described in the previous paper by Dr. Beyers citing the various balanced microcosms; the relative ease of obtaining systems with mutliple, self-selecting species; and their day night coupling sequences. Some other projects reported at this symposium not yet entirely balanced conceptually fall into this

TABLE 1

Magnitudes in existing solar-based ecosystems pertinent to human carrying capacity (organic imports and exports minor)

	Transient state[a]	Climax, unfavorable boundary conditions[c]	Climax, favorable boundary conditions[b]
Efficiency of gross photosynthesis in percent of visible light at high light intensities	0.1–5%	0.1–5%	5–10%
Species diversity, species per thousand individuals as an indication of circuit complexity	2–15	1–10	15–60
Percent of system gross photosynthesis used for system maintenance work	2–90%	100%	100%
Percent of system respiration due to one large consumer species	2–10%?	?	0.1–2%

[a] Examples: new algal culture, young southern pine forest, newly seeded fish pond, successional grassland with locusts, young agricultural planting without cultivation and poisoning.

[b] Examples: coral reef, rain forest, balanced laboratory aquarium.

[c] Examples: hot springs, brine system, desert.

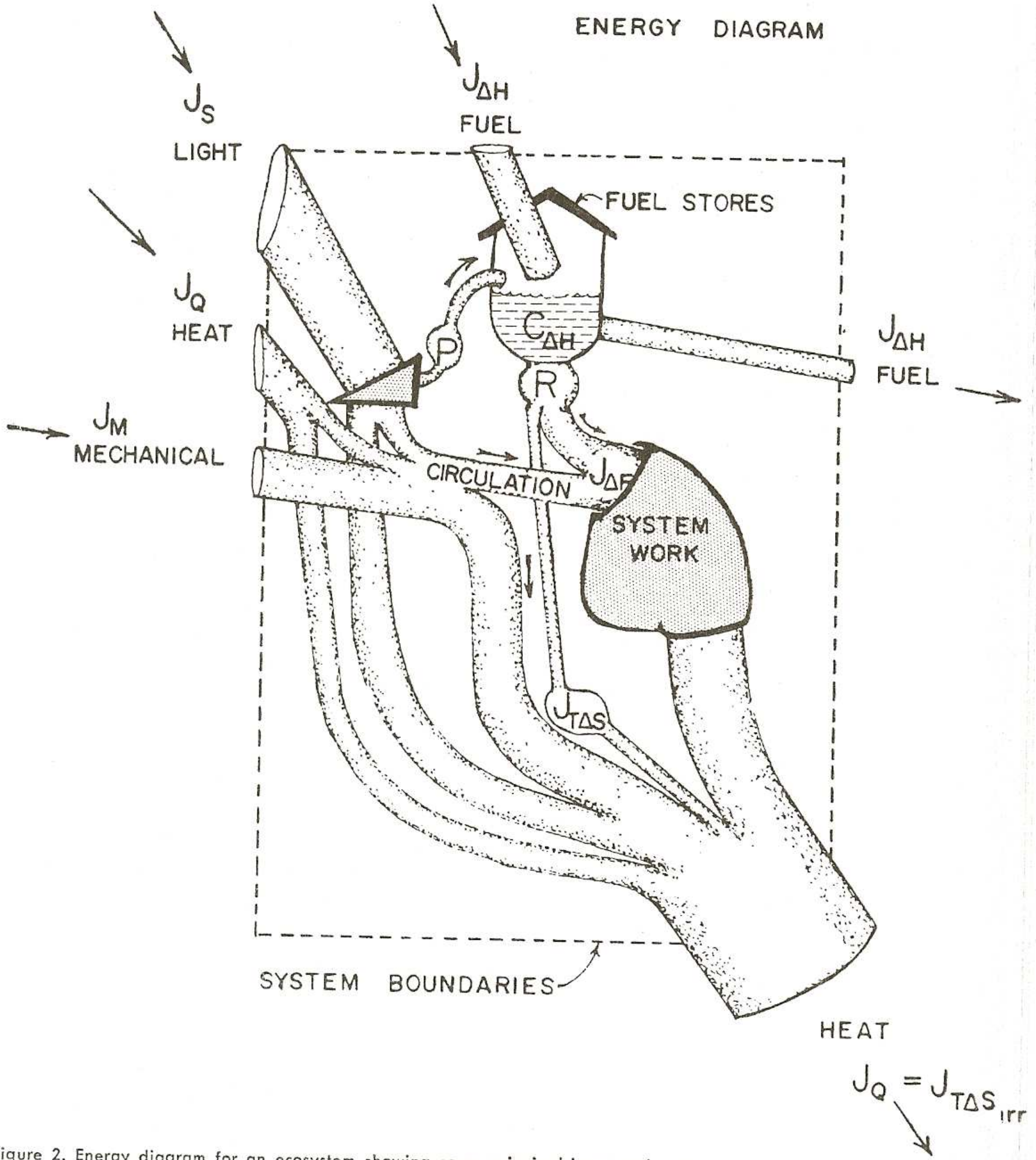

Figure 2. Energy diagram for an ecosystem showing some principal input and output energy fluxes (J's) illustrating both the first and second laws of thermodynamics as applied to ecosystems. P, Gross photosynthesis; R, Total respiration; F. Free energy; H, Heat of reaction; S, Entropy.

classification, although in practice they belong in the type discussed next.

For completeness, the general case is also included (Fig. 1A) in which both remote supply and internal recycling occur, a type important in ecosystems on earth such as the coral reef and the rain forest. In these two examples the internal cycle predominates on solar energy, but a few critical supplies of material are regularly imported (open sea flow and forest rain), without which much lower efficiencies might prevail.

Remote versus Autonomous Energy Support

In Fig. 3 energy flows for systems of relative remoteness from a parent system are diagrammed. One is in almost complete autonomy with separate solar free energy

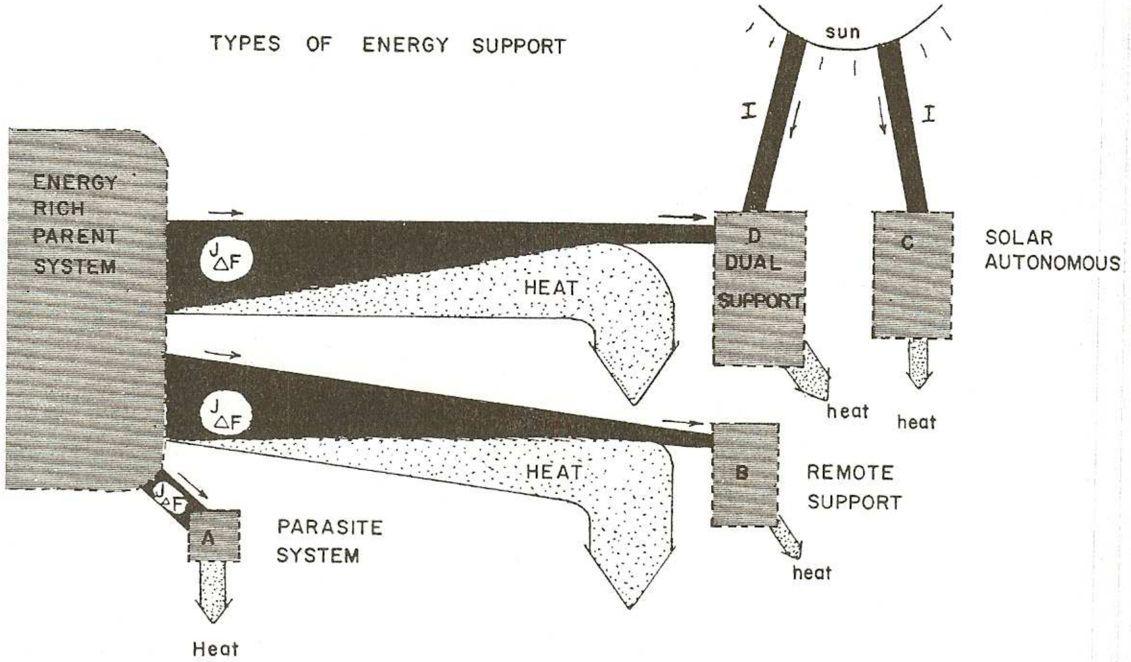

Figure 3. Comparison of 4 types of ecosystems in relation to the flux of free energy available at a distance from an energy rich parent system.

flux (C). The other systems involve subsidiary sub-systems at varying distances from the parent source of materials and energy.

With the closely adjacent parasite subsystem (A), support from the main system is economical and competitive relative to alternative independent systems at that point. Because most of the functions are still carried on within the parent system, the subsystem (A) can be of minimal size for its mission. The parent-subsystem relationship is analogous to a parasite-host relationship in which rudimentary parasites lose much of the functional biomass during evolution.

In subsystem B, however, with remote support, the flux of free energy that must be spent in work of transportation, control, information transmission, redundancy, and other functions of remote integration become very large. Not only is the system highly expensive relative to the alternative closed system (C), but at sufficient distance, the energy and material flux that can be brought to the system per time, regardless of the initial free energy flux from the source system becomes less than that available from the local source.

System C is limited to its autonomous solar energy flux with only communication from the parent system. At the distances at which maximum possible remote transport of net energy becomes less than the autonomous energy power supplied, the autonomous system becomes more feasible. Thus the autonomous system serves as a limit to theoretical computations of feasibility of remote systems.

The system D in Fig. 3 is the ecosystem resulting from a combination of remote and autonomous power supplies. Whereas a combination may be necessary where the maintenance costs are high, there may be a danger of extinction if the carrying load is designed for full power instead of for the minimum power of 100% reliability, using the remote and autonomous sources as complementary alternates.

The regimes of productivity in many marine bays alternate between dominance by remote energy flux from flooding rivers and autonomous existence on solar power. In such dual support systems there are mechanisms for retention of representative circuits (species) of one system regime during the predominance of the other as well as circuits capable of handling both types alternatively, as for example, the shifting and omnivorous food habits of some estuarine species worked out by Darnell (1960) for Lake Pontchartrain, Louisiana.

Whereas, small system size was possible for the closely adjacent subsystem, since only parts of the total functional circuits were required in the remote package, the autonomous systems C and D must carry almost the entire circuitry necessary for maintenance and function, with the size necessarily larger.

The distance at which the autonomous system becomes equally competitive with the remote support system is the distance at which the flux of net free energy from the parent ($J_{\Delta F_p}$) reaching the remote point ($J_{\Delta F_r}$) is equal to the autonomous flux of available power input ($J_{\Delta F_a}$). Thus the autonomous system becomes equally feasible in energy terms when expression (1) holds.

$$J_{\Delta F_p} - W = J_{\Delta F_r} = J_{\Delta F_a} \qquad (1)$$

W is the flux of free energy that must be spent into heat during work of transmission between parent and remote system. Obviously, only very energy rich systems can spend large sums for W and still be competitive unless the remote subsystems are part of the competitive necessity. The application of this function to present world energetics in political affairs of large economic orbs and their satellites is obvious, but not the subject of this symposium. The function is also analogous to the support of basic research institutes like marine stations on remote islands. The equation also provides means for relating energy budgets to the diversity of island faunas as in the Caribbean.

At any spot, whether one considers isolated reefs, islands, bays, or space systems, the kind of regime and its character as classified in Fig. 3 may be computed from the available free energy flux from the parent system, the available free energy in the autonomous location, the work function of energy transmission, and the work cost of maintenance. Obviously, when the work flux of maintenance is greater than both energy fluxes together (Fig. 3D), there can be no system at all.

One of the important contributions of ecological theory to system-subsystem relationships was made by Preston (1962) in showing convincing evidence that the diversity of species (representing complexity of the organization of ecosystem circuits) can be very large in subsystems which are merely statistical subsamples of the large parent systems. Preston used data from island faunas close to a mainland. Islands of similar size remotely located had a much smaller lognormal grouping of species diversity consistent with autonomous existence. In such islands the transmission of power from the parent is mainly by the movements, migrations, and radii of operation of the larger birds, insects, and fishes as paid for from food sources of the parent system. The simple cave faunal circuits maintained on guano of resting bats that feed outside are a good example of a remote subsystem and its necessary simplicity.

Applying these earth precedents to the remote ecosystem problem in space, one must expect and plan for a much simplified functional operation in the autonomous system relative to the near-subsystem on a parent flux basis yet more complex than some present prototypes as discussed below. The ratios of the numbers of species and distributions provided by Preston probably are the ratios of numbers and kinds of effective circuits and adaptations possible whether engineered biologically with species or engineered mechanically and electronically.

Whether systems of remote maintenance and support can be achieved with sufficient reliability and economy at planetary distances remains to be determined, but the known performance of small closed autonomous systems provide the limits and goals for those attempting the development of the remote support types as in Fig. 3.

It should be realized that the balanced ecosystems already exist with self-regulating controls, maintenance, reproduction, and recycling as discussed by Dr. Beyers. The packaging for planetary transmission and housing may be a far more feasible engineering job than attempting to repeat in metal the multitude of evolutionary steps in the development of the ecosystem over the long period of earth history. Whether one regards the closed ecosystem as the ultimate remote system or merely as an engineering goal to beat, consider next some processes of the ecosystem which determines its maximum capabilities.

Photosynthetic Efficiency of Adapted Systems

The tremendous efforts in science at this midcentury to achieve a maximum utilization of the sun's energy have been accompanied by very great dreams of power output that are somewhat comparable to the hopes for heat engines in the last century before the impact of the Carnot cycle and the second law of thermodynamics. Especially regarding photosynthesis for feeding and oxygenating man in space as on earth, there has been no general realization of thermodynamic limits beyond which no improvement is possible.

For example, Bonner (1962) recently sought new reasons why higher efficiencies were not being found in nature or developed in the experiment station. He believed that the plants were adapting to an average low light intensity and thus were not adapted to a rarer high light intensity. Farrington Daniels (1956, 1961) writes that higher outputs than obtained in nature are possible, and that some high efficiences found at low light intensity can be developed for full insolation flux. He uses yields per volume in thin layer algal cultures as potentials for deep cultures.

Duysens (1958) used an abstract model to compute the temperature equivalents of fields of visible radiation and the limiting reversible Carnot efficiency of around 70% for processes like photosynthesis in which radiation energy is ultimately dispersed at an ambient heat to an environment of about 300° C. However, this reversible limit was discussed in an irreversible flow. By implication useful conversions of this magnitude may be considered feasible by his readers.

Blagergroen (1960) like Burk and Warburg, at times in the past, continue to defend the manometric transients as indications of 50 to 90% ultimate potential conversion in steady state in spite of Emerson. Kleiber (1961) while discarding all of steady state thermodynamics with the statement, "The law of entropy has been developed for closed systems and may not directly apply to open systems such as animals"; gives the potential carrying capacity of one human on algae as one square meter based on a 50% efficiency. These discussions extending low light efficiencies and overestimated efficiencies to high light loads reflect little concern with the speed-power reciprocity principle in energetic coupling.

Even among the cautious, the existence of a principle is being overlooked. For example, the volumes on photochemistry, photochemical apparatus, and primary photosynthetic reception (Augenstine, 1960; Brookhaven symposium of 1958, Gaffron et al., 1957; Daniels and Duffie, 1961; and Heidt et al., 1960) have only a few guarded words of the consequences of power selection as in Trivich, Flinn, and Bowlden (1955) in a discussion of photovoltaic cells.

Lumry and Spikes (1960), for example, write, "Efficient utilization of energy means utilization with as little spontaneous entropy production as possible. The most efficient utilization occurs, of course, in a reversible equilibrium. However, since rate of reaction is also an important factor for living organisms some compromise between infinitely slow equilibria and entropy wasting fast reaction is necessary." These authors thus put the focus on the general times speed regulator principle which we offered earlier (Odum and Pinkerton, 1955). The requirement that greater and greater fractions of available free energy must go for "Entropy Tax" into heat when systems are geared for faster rates results in theromdynamic requirement that efficiency decline as power increases in a relationship that reaches a peak power when the efficiency is neither at its lowest or highest among possible load settings. It is this maximum power setting that tends to result in ecosystems because of natural selection. If organisms which survive are those with maximum useful power output for constructive purposes and since there is a reciprocity between power output and efficiency, successful surviving systems will tend to possess the certain moderate efficiency that is much less than that possible when the system is run slowly.

It seems to this author appropriate to unite the biological and physical traditions by giving the Darwinian principle of natural selection the citation as the *fourth law of thermodynamics,* since it is the controlling principle in rate of heat generation and efficiency settings in irreversible biological processes.

Two examples may be cited to illustrate

the operation of the principle of power-efficiency reciprocity selection in systems operating on solar energy. For both the graph of power and efficiency is of the form given in Fig. 4.

A selenium photometric cell produces a separation of electrons from "holes" when light is received and may drive an electric current in an external wire connecting top and bottom surfaces. The power output as a function of load was studied by Billig and Plessner (1949). Their data provide a curve of power and efficiency, when plotted, like that in Fig. 4, with a relatively low efficiency at maximum power loading. At a high resistance loading of the external circuit efficiency becomes maximal as the power output approaches zero. At a very low resistance loading (short circuit) the process is very rapid, but the power again approaches zero.

Another example is the algal mat ecosystem found in shallow briny bays of south Texas. When platinum electrodes are placed above and below the mat on its oxidized and reduced surfaces respectively, the mat delivers photoelectric power like that of a solar cell, the photon reception being mediated through the semiconductors of the plant chlorophyll in the living ecosystem (Armstrong and Odum, 1964). The curve of watts output with varying external load resistance is like that of the selenium cell (Fig. 4).

Since the power-efficiency reciprocity in systems is general for open systems, the thoroughly established facts concerning the photosynthetic efficiency in ecosystems should not be unexpected. Maximum output of gross photosynthesis at daylight light intensities is of the order of 5 to 10%, values representing the peak selection point in Fig. 4. The increase in efficiencies that one gets with lower light intensities is illustrated by Manning, Juday, and Wolf (1938) for *Chlorella* culture and by Edwards and Owen (1962) for a stream. These curves represent the left arm of the curve in Fig. 4. The many experiments of a preceding decade on efficiency of algal conversion at very low light intensities aimed at obtaining maximum quantum efficiencies were also in the left region of the graph.

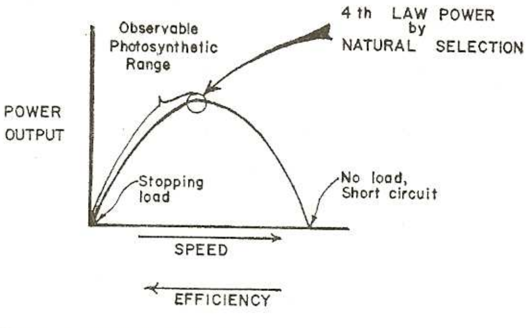

Figure 4. General form of the graph of power output and efficiency of energy transfer as the speed setting of load and input process is varied. See text for photocell and ecosystem examples. Darwinism is suggested as the 4th law of thermodynamics because of its regulation of the rate settings in nature.

The implication of the efficiency-power reciprocity principle for space ecosystems is that the limit for photosynthetic power conversion may have been selected for and achieved long ago in the many optimal ecosystems of long evolutionary age. The wild optimism cited in some photochemical and physiological writings about possibilities for achieving higher efficiencies are contrary to Darwinism and often made without an understanding of the reciprocity principle.

It must be concluded that there is no evidence whatever that any ecosystem can be constructed based on an efficiency at full daylight input greater than those which already have millions of years of competitive experience. For purposes of estimating the carrying capacity for man in space, 5% of visible light received is used for gross photosynthesis.

Maintenance Demands on System Capability

The next question in estimating closed ecosystem capabilities for man is how much of the photosynthetic output must go for system maintenance, and how much is left for man? Some inferences may be obtained from existing ecosystems on earth.

Maintenance Costs at Climax

In comparing the efficiencies of things engineered by man with those of self maintaining systems, the costs of maintenance are often overlooked so that the independent natural system may seem less efficient. For example, the efficiency of an automobile is sometimes stated as 20% work output per fuel consumed which represents its output not including cost, depreciation, or maintenance. If one takes the dollar value of the depreciation and/or repair, converts it to gallons of gasoline, and refigures the car output, a figure of about 5% results making the steady state behavior similar or less than that of some comparable biological systems. Very young embryonic organisms similarly show high growth efficiencies up to 66% (Needham, 1931) before their respiratory maintence costs have to rise.

The climax ecosystem is the only system so far known which is completely self sustaining and stable. Such systems as the coral reef, Silver Springs, certain forests, tropical seas, put almost all of their metabolism into maintenance. Their entire respiration goes for replacing parts and rearranging structures that are dissipated and disarranged by the inherent entropy increasing tendencies of the environment on microscopic and macroscopic scale. In such systems the organizational work is the respiration and is balanced against disorganizational trends. Thus one has available factual data on total maintenance capabilities where one may suspect maximum performance is already developed.

The respiration of such communties includes that for maintaining a large photosynthetic apparatus, usually with vertically stratified structure plus a large specialized component of animals and microbes for special waste recycling in the same ratio as used by the plants plus species as regulators and servo-circuits. The total respiration of such systems has a special theoretical significance as the free energy flux for maintaining low entropy state of the biological structure. The real costs of ecosystems at climax range from around 1 to 30 gm/m^2/day oxygen (4 to 120 KCal/m^2/day ΔF) and occasionally higher. These are the minimal costs for space capability.

Hidden Cost of Maintaining Artificial Algal Systems

A self sustaining escosystem such as a sea gyral or a pond can be considered as made of two portions; the first includes the rapidly growing plants which have a very high ratio of gross photosynthesis to self respiration; the other includes all the rest of the organisms, older plants, microbes, animals, etc. One may consider that the first part is making the food, the rest is doing the maintenance, reproduction, controls, recycling, regenerating, protecting against competition, providing three dimensional structure, and all the other work requirements of self-sustaining survival. Most of the gross photosynthesis by the first part is required for the respiration of the second.

When an artificial algal turbidistat system is constructed and nurtured by the experimental scientist, he substitutes for part two: human subsidies, stirring, parts, nutrient supplies, waste removal, controls, structure, protection, and other energy costing aids from a fossil-fuel based industrial culture. By ignoring his tremendous hidden subsidies, it is possible to compute a high efficiency of net production. Yet the maintenance is being supported artificially with outside fuels instead of with self respiration in the self-sustaining ecosystem. For example, Wassink (1957) gives a very misleading picture of the relative efficiencies of natural world ecosystems as compared to agriculture and mass algal culture by comparing net productions of self-sustaining ecosystems with artificially manipulated systems, omitting the contribution of man, his fossil fuel culture, and the vast efforts necessary to keep the artificially simplified systems temporarily competitive.

Whereas the maximum gross production rates approach similar values in natural ecosystems, agriculture under the best conditions, and in the best mass algal culture as about 40 gm/m^2/day oxygen, the net yields are made to seem greater in the algal systems and agriculture by ignoring the greater hidden energy subsidies that make respiratory maintenance unnecessary. The general public has been misled on these relative potentials by enthusiastic writers for years.

In appraising the potential costs of closed system designs one has the alternative of paying for a complex ecosystem with self maintenance, respiration, and controls in the form of multiple species as ecological engineering, or in restricting the production to some reduced system like an artificial algal turbidistat and supplying the structure, maintenance, controls, and the rest of the functions as metallic-hardware engineering. Where the natural combinations of circuits and "biohardware" have already been selected for power and miniaturization for millions of years probably at thermodynamic limits, it is exceedingly questionable that better utilization of energy can be arranged for maintenance and control purposes with bulky, nonreproducing, nonself maintaining robot engineering. From difficulties in sustaining simple systems discussed in this symposium, it is even doubtful if safety can be achieved at all without the regular ecosystem's complementary species.

There is a large area for metallic and ecological engineering to adapt existing biohardware units to special purposes for which selection pressure has never before been brought, but this endeavor is envisioned within existing ratios of respiratory maintenance.

To indicate more precisely what the respiratory maintenance expenditures are supporting that is necessary in a biological system besides man, consider biological circuitry.

Circuit Diversity and Species as a Control System

The circuits of nutrients are insulated, controlled, relayed, amplified, manipulated in time lags with storage, delayed by inductance-like lags in food flow, and guided with genetic information programs on behavior by the species which are to the ecosystem what the electrical parts are to the electronic system. Many of the biological controls are far in advance of those in electronic systems, since they already involve self-reproduction and maintenance. The relationship of types of main circuits (species) to circuit components (individuals) tends to be logarithmic as studied by many groups of ecologists with a large literature.

It is a familiar ecological principle that when complex climax systems are disturbed, removed, or otherwise disarranged, the species diversity is diminished and a substitution of more generalized species replaces the complex structure temporarily. Just as in electronics, precision controls require a large circuit-control structure, so the precision control of the climax system also requires extensive species and complex maintenance structures. A beautiful illustration of metabolic homeostasis with varying temperature by balanced aquaria was recently reported by Beyers (1962).

Thus if one is to maintain an ecosystem containing man that has the reliability, precision self-regulation, and safety desirable and necessary, it must have a full complement of other species. The alternate of reducing the species to just two, man and the plant food species, requires substitution of extensive hardware engineering to replace the already existent biological circuitry.

If proof is necessary, one may cite a dozen types of balanced ecosystems under laboratory manipulation as reported in Dr. Beyer's paper on day-night coupling systems. One might ask, how many balanced two species systems are now self-regulating and reliable?

If one sets out to eliminate the cellulose, the structure, the storage reservoirs (acting as condensors), the alternative species, etc., one is setting out to eliminate the ready-made engineering system. One cannot do this without compensating with man-made engineering to replace the functions. The effort is comparable to building a television set by eliminating all but two wires and two parts, ignoring the rest of electronic capability. It is significant that where some progress is made in waste regeneration in a closed system are discussed at this symposium by Golueke and Oswald, the competitive complex of species of micro-organisms has been retained, derived from self-sustaining ecosystems already adapted to sewage.

Just as the wires and parts of any electrical system must, above all, be joined to the principal function transducer, so the circuits and parts of the mainly biological circuitry must be compatible with the unit of principal importance in this class of systems, man. No necessary circuits should be left open or with inadequate conductivity. Thus the input circuit leads of man as a system part must be considered. These taps are his nutritional requirements.

Trophic Position of Man in System Circuits

The trophic position of man in ecosystems has changed and evolved in various ways from the nomadic hunting society to the agricultural community, to the multiple omnivorous nutrition of the modern world. The diversity with which man shifts from high to low trophic positions is part of his means for fitting into more than one kind of ecosystem. In spite of this diversity of role, minimal requirements are well known in his much-studied nutrition. He cannot survive on only one food circuit unless it is at a higher trophic level (eating tissue similar to his own), thus already involving the convergence of flows from more than one kind of plant producer. Dr. Myers (1960) has already shown some of the problem with coupling a consumer and one species of producer in the mouse-Chlorella combination with respiratory quotient difficulty. It is easier to do the whole ecosystem than attempt it in parts in this way.

As well known ecological principles specify, one loses 90% of the free energy flux with each trophic level, so the possibility of coupling man to a long trophic level of two or three steps (producer, herbivore, carnivore, and top carnivore) automatically leads to a very low ratio of human metabolism to total metabolism, a large area requirement, and a fully developed climax ecosystem requirement.

Alternatively, one may set man in a primarily herbivore role, but must introduce great diversity of producers and a large system of maintaining this pattern in order to gain adequate nutrient variety. In any event one must consider the diversity and extra species for nutritive reasons as well as for the maintenance-control reasons cited in previous paragraphs.

If it were possible to evolve human genetic-biochemical varieties rapidly there would be the interesting possibility of dividing biochemical circuit jobs among men just as the finches on Galapagos Island eventually evolved a division of function from a single species. Thus a closed system might be involved with a human rice eater, Chlorella eater, a waste eater, a processor, a separator, etc. In theory one might substitute the various specialized humans for the necessary species to fully function the system.

Man does this type of specialization rapidly in his industrial economy but evolves his plastic brain programs along with changeable fossil fuel-based machinery as the means for specialization but his own nutrition is not so plastic. Whether one can ever exploit biochemical variation among humans to the extent that other species of organisms could be supplanted in a closed ecosystem remains to be seen.

Enough is known of man's role in past ecosystems to be sure that some food circuit diversity will be necessary for nutritive reasons. It will be unwise as yet to assume lower ratios of species and total metabolism to accompany man than have ever been achieved in prior precedence on earth.

Carrying Capacity for Man

In preceding paragraphs, two practicalities involving capabilities and ecosystem size have been emphasized:

1. The maximum possible photosynthetic power output (gross) may have already been developed in existing ecosystems which occur with an efficiency of only 5 to 10% due to the thermodynamic reciprocity of power and efficiency in a two stage coupled energy transfer.
2. To retain ecosystem stability, permanence, safety, self-reproduction, complete nutrient cycling, and self-maintenance; a complex control system of biological circuits must be retained along with man. The cost in existing ecosystems is an expenditure of all but about 2% of the photosynthetic production on respiratory maintenance of components of the system other than single large consumers.

In Table 1 are the properties of ecosystems that provide these estimates of capability of beautifully miniaturized biological circuitry. Is it conceivable that the weight, costs, stability, and permanence of metallic hardware can be made to compete?

The ultimate safe efficiency of supporting man on photosynthetic based energy complete with an ecosystem run on biological circuitry is 0.1 to 0.01% of the visible light intensity (5% x 2%). The distribution of the energies in such a system is represented in Table 2 in proportions found in known self-sufficient ecosystems.

If one allows a substantial area-based gross photosynthesis such as is sustained in climax ecosystems, better than most agriculture, as 10 gm/m^2/day oxygen or organic matter, one obtains more than 2 acres of area per man. These realistic computations based on actually balanced systems require substantially more area than that given by most previous authors. Some of the authors overestimate the possible gross photosynthetic efficiency that goes with maximum power

TABLE 2

Free Energy Budget for a Self-Maintaining, Light Supported Closed Ecosystem at Climax

	Cost	Remaining 100%
Entropy Tax on Optimum Gross P	95%	5%
Organizational Maintenance Work (Respiration at Climax)		
Plants	2%	3%
Microbes	2%	1%
Other Animals	0.9%	0.1%
Large Animals	0.09%	0.01%
One Mammal Species	0.01%	0

selection. Others base their estimates on converting most of the gross production into metabolism of man, thus eliminating the system's necessary functions, or use artificial algal system net yields that also hide the sustaining costs.

Since there is abundant anthropological precedence for man in self-sustaining complex ecosystems, why should one even try to get the electronic-metallic-mechanical—and as yet nonexistent—mechanisms for man into less space than biocircuits whose splendid miniaturization is far ahead of electronics. To expect to run enough oversized metallic robot substitutes to manage the system on dilute visible energy is thermodynamic science fiction. The biological hardware for doing the job is at hand, but we should have no illusions about reducing the solar flux area. The final question is, how does one proceed with ecological engineering of a closed ecosystem including man?

Multiple Seeding in Ecosystem Engineering

The methods used for achieving the balanced ecosystems studied at the Institute of Marine Science in recent years are simple but not elegant. Multiple species are taken from environments in nature that are similar to that being designed. For example, in engineering a brackishwater system, brackishwater bay organisms are seeded into a tank. Immediately the species added begin to readjust, with most types disappearing. The nutrition of decomposing individuals develops a characteristic recycling mix. The remaining species develop the usual logarithmic ratios of their individuals (circuits). Metabolism usually falls at first, with respiration often exceeding photosynthesis. In about two weeks, with continual multiple species seeding, the new ecosystem begins to emerge as indicated by accelerating photosynthesis, an approach towards a balance of P and R and the predominance of several species at each trophic level. The system is now competitive, self-sustaining, and highly metabolic. Duplicate systems are made by mixing tanks for a day every week so that the tendencies to develop unique systems are neutralized by the thorough mixing. Such ecological engineering systems have now been much studied metabolically as illustrated by papers by Odum and Hoskin (1957), Beyers (1963a, 1963b, 1963c), and Odum, Siler, Beyers, and Armstrong (1963).

The terrestrial environment has not been tested in this way, however, because of the larger size necessary for enclosure plus the expensive refrigeration problems in enclosing a closed terrestrial system. Presumably the methodology is similar: seed with multiple species, reseed with any species particularly desired until the others adapt. Continual seeding of one species eventually controls the nutrient ratio in favor of the species being seeded even if there is some mortality at first due to poor adaptation. Under continuous seeding pressure, eventually the nutrient ratios become that of the seeded species and hence the other circuits become geared to provide that ratio (Redfields principle as first applied to the North Atlantic Ocean).

The challenge of ecological engineering for men in a remote system may be met with a similar methodology. Introduce men into a closed system of 2½ acres per man along with multiple compatible species, including agricultural varieties consistent with the simpler forms of agricultural economy as in South America. Let them adapt. Continue the seeding pressure until a self-stabilized, fully competitive system begins to be sustained. One might have to bail out the human components from time to time gaseously, nutritionally, or psychologically, but eventually judging by experience with the aquatic systems, biogeochemical circuits would become organized by selection, and the constant pressure of maintaining a man present would provide a return circuit for him as part of a new climax ecosystem for space. Success at this would still leave capsulization, temperature controls, and transportation to metallic engineering, quite formidable tasks in themselves.

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