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THERMODYNAMIC CONSIDERATIONS IN THE SUPPORT OF LIFE FOR LONG SPACE VOYAGES

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ABSTRACT

The purpose of this study is to specify the essential requirements for the maintenance of life, particularly human life, on isolated space missions of long duration. The achievement of that purpose is approached via an extended irreversible thermodynamics. It is suggested that this science is the only one capable of performing that service of characterizing the essential variables needed for autonomous survival. The character of a four trophic level system is arrived at. Questions of stability are discussed.

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A PHYSICAL INTRODUCTION

While life on earth has a long 3-4 billion year history, its success has been based on the slow play of a limited number of natural forces on a particular group of chemical materials under specialized physical conditions. The problem posed for this study is to determine more localized conditions, if not the most localized conditions, under which a life system (human) could be self-supporting. While the initial period of time in mind (months) seems far removed from the planetary scale (which may be up to 4 billion years for all of life; 0.5 billion for complex life forms; 0.2 billion for mammals; 10 million for hominids; down to 50,000 - 100,000 years life scale for a species), clearly the extension to space flights of years and even generations time scale is envisioned. At a 'natural' time scale of generations, distinctions between the planetary problem of life support and a local space vehicle have diminished, except for the scale of size and number. However the localized problem is generally much more precarious because variations or fluctuations which can easily be tolerated at large scale can prove fatal at small size. One notes that this continent received a number of waves of European settlers who had to develop many colonies before their viability was assured.

Clearly the problem of leading people into new territories has an ancient history, likely involving the myths of every culture. A confrontation is thus forced as to the conditions for successful settlement. Are the requirements divine intervention, heroic father or leader figures with some profoundly deep, pragmatic, or lucky grasp of the available opportunities, sufficiently repeated efforts until some beachhead colonies take, or are the requirements now capable of the parsimonious specification that more modern science might promise?

Recognizing that living species diversify and explore territory as what appears to be part of an almost compulsive thrust to maintain and extend life, and that man, the explorer, exemplifies that drive very well, it has been interesting to note the appearance of the scientific problem within the past generation. It is especially interesting to watch the focus of problem transfer to and grow within NASA's research mission, especially interesting in an applied scientific sense because the goals do ultimately relate to social needs.

To highlight some minimal foci that have brought the problem within a scientific scope, rather than a religious, social science, psychological, or accidental problem, the following are suggested:

Bernard and Cannon's notions of life as an internally regulated process;

Miller-Urey's demonstration that organic synthesis was not a terribly difficult atmospheric process;

> Morowitz' argument that tied the energetics of life processes to a photochemical reaction and thereby to a particular range of stars;
>
> Goodwin and Iberall's notion that life processes - cell to organism - were conducted thermodynamically as dynamic limit cycle ('clocking') processes;
>
> Hart's modeling of the chemical evolution of the atmosphere, which can lead to life, whereby the planet earth's resultant is narrow and fitting both as to the star, the planet position, and its materials.

The latter four studies, all in the last two decades, all with NASA support or connection, are indicative of the new scientific momentum to provide scientific specification of the conditions for life survivorship in the large.

The narrower thermodynamic problem may be viewed as beginning with Lavoisier (life's use of oxidative processes for energy), more narrowly with Rubner at the turn of the century, who demonstrated the thermodynamic equilibrium in living organisms by whole body calorimetry. The heat of combustion of foodstuffs, as fuels, in the chemical laboratory was shown to be the same as the metabolic power released by the whole body, when the body results were collected over a period of days (except for a small anabolizing fraction of protein).

Some very brief introduction to a clinical-experimental outlook toward nutrition and metabolism may be garnered from Section Six, Nutrition and Metabolism in (1); also see (2). Some private notes have been developed by a biological colleague as part of the biological system's dialogue begun in an earlier NASA study (3); see (4). The subject will be returned to the more detailed nutritional issues after a more general discussion of survivorship.

Survivorship, in a biological sense, is not that of the individual. It is more a concern of the 'race' (that portion of a species which lies within a common breeding pool), and, beyond, of the species. In highly visible social efforts, unacceptability of individual mission failure requires a large and costly control schema which natural evolving systems eschew. More commonly than accepting the notion of such complete controlled support that a mission cannot fail, the general of an Army operates with an acceptable notion of mission risk, as does the surgeon, as does the American driver when taking his or her automobile on the highway.

Thus it is apparently more valid science to focus the scientific survivorship problem on self regulatory results (so-called open loop regulation) rather than highly controlled mission results. In essence, the question addressed is what is an ample strategy for mission survival according to more normal expectations?

This is more the question of the maintenance of generation to generation survivorship - what is required to have a self-regulatory environment in a space mission that would persist indefinitely? It is not the question of making one beachhead on a new land, e.g., guaranteeing Man's successful penetration of the America's at one particular time, as compared to Man wandering into the Americas, say, at various times between 50,000 and 15,000 ybp; or European Man's subsequent penetration in 1500, and requiring trials by a number of colonies rather than being forced to replicate single colonies with little margin of error.

There is a physics for persistent ensembles of atomistic-like entities ('atomisms'), in this case living organisms, in fact people. That physics is known as statistical mechanics. When that subject deals with the total conditions for motional persistence, not only local equilibrium, it becomes irreversible thermodynamics. As applied to an entire ensemble of atomisms distributed throughout a space, it becomes a field thermodynamics. (The hydrodynamics of a flow field illustrates such irreversible field thermodynamics.) Minimally that subject seems concerned with the flow of energy. But it is more than that. Via statistical mechanics, thermodynamics deals both locally and in the large with all of the essential conservations that take place upon atomistic interactions, e.g., the fluctuating collisions. That physics has been discussed in detail elsewhere (5).

As a brief summary:

There are simple systems:

one component - These exhibit conservations of mass, momentum, and energy (e.g., energy is unchanged locally by each collision).

many interacting components - These exhibit conservations of each mass species, conservation of momentum for each mass species, conservation of energy.

There are complex systems:

nonliving - These exhibit conservations of individual mass species, conservation of internal actions, conservation of energy.

living - These exhibit conservations as above; also conservation of population in a breeding pool.

Thermodynamics of a Simple One Component System

The fundamental characteristics of a thermodynamic description can be demonstrated for the simple one component system.

1. Conservations - Mass, momentum, energy. When simple atomisms (e.g., molecules) collide, these three quantities are conserved.

2. Distribution functions - Suppose a container is filled with these atomisms so as to form one homogeneous phase, e.g., a compressed gas phase, then there will be independent distribution functions which develop out of the conservations. These will be statistical measures of the ensemble that develop because of the interactive mechanics among the individuals. Note should be taken of a recent proposition (6) that continuum-like mechanics implies thermodynamics. The sustained motion is supported from outside, e.g., the thermal energies by radiation from the wall; or a universal zero point quantum mechanical energy of a nonthermal character.

mass - if m_i is the particle mass of the i^{th} particle (all identical to m), then the mass distribution function is

$$\rho = \frac{\sum_{i=1}^{n} m_i}{V} = \frac{m \sum_{i=1}^{n} 1}{V} = \frac{nm}{V} = \frac{M}{V}$$

a constancy of mass density throughout the volume V (n particles of mass m, making up a mass M). Each region of the container has the same density.

momentum - if $m\bar{v}_i$ is the vector momentum of the i^{th} particle (its x,y, z components are mu, mv, mw), then the condition for the constancy of momentum of the isolated ensemble (taken as zero in the observational frame) is

$$M\bar{U} = 0 = \Sigma\, m\, \bar{v}_i = M\, \Sigma\, \bar{v}_i$$

$$M\, \Sigma\, u_i = 0$$

$$M\, \Sigma\, v_i = 0$$

$$M\, \Sigma\, w_i = 0$$

energy - if $\frac{m\bar{v}_i^{\,2}}{2}$ is the kinetic energy of the particles, then

$$E = \frac{1}{2}\, \Sigma\, m\, \bar{v}_i^{\,2} = \frac{1}{2} M\ \Sigma \left\{ u_i^2 + v_i^2 + w_i^2 \right\}$$

where E is the total kinetic energy of the system (it is assumed in this simple example that there is no other possible energy storage).

These are the only constraints; they emerge from the summational invariants. But they do not answer how the velocity is distributed among the ensemble. We surmise that the momentum per unit volume is the same (zero) throughout, and the energy per unit volume (E/V) is the same throughout. But how do the velocities distribute among each other in any local domain? That is the problem that statistical mechanics furnishes an answer to. These statistical measure

$$\Sigma mn, \quad \Sigma mnu^1, \quad \Sigma mnv^1, \quad \Sigma mmw^1, \quad \Sigma mn\ (u^2 + v^2 + w^2)$$

are co-constrained moments, and that statistical fact provides the distribution function. Since these statistical measures are independent, their associated probability P can be determined. Taking the logarithm of the probability describing the co-constrained distribution function, it must consist, at most, of a linear association of these independent moments;

$$\ln P = Amn + B_1 mnu + B_2 mnv + B_3 mnw + C_1 mnu^2 + C_2 mnv^2 + C_3 mnw^2$$

with undetermined constants A, B, C.

If the ensemble is isolated, mn is a constant, and if the field is isotropic (no directional properties) as well as homogeneous, the indifference of distinguishing velocity components permits assuming $B_1 = B_2 = B_3$ and $C_1 = C_2 = C_3$. Rearranging the form, with new constants, A, C, u_o

$$\ln P = \ln A + C \left\{ (u - u_o)^2 + (v - v_o)^2 + (w - w_o)^2 \right\}$$

The first moment is fixed by choice of axis, and the condition of isolation to

$$u_o = v_o = w_o = 0$$

Thus

$$\ln P = \ln A + C\ (u^2 + v^2 + w^2)$$

In order to identify C, it is common to use the strategm of putting this ensemble and its enclosure in contact with an ideal gas thermometer, which establishes an open contact with a temperature potential. Then the constant C is identified with m/2 kT, so that

$$\ln P = \ln A - m\ (u^2 + v^2 + w^2)/2\ kT$$

Maxwell's normal distribution of velocities. In terms of the kinetic energy ε of the particles

$$\ln P = \ln A - \varepsilon/kT$$

The Maxwell-Boltzmann distribution.

While the example given was the simplest possible derivation of the distribution functions, it exhibits all of the essential characteristics of a derivation. The distribution functions characterize how all the quantities which are conserved upon interactions distribute themselves in the phase space of the ensemble. In this example, in each local homogeneous region, the mass or number density is constant, the average momentum is zero, the kinetic energies are distributed exponentially with the highest probability associated with rest. (The velocity itself is distributed normally around zero.)

The latter result should not be misleading. It immediately exhibits some sophisticated consequences. One is confronted by two opposing notions - one, that at the equilibrium state of the ensemble, motion should tend toward rest; that, in fact, is the mean velocity state. But on the other hand, the open supply of potential energy should result in some significant sustained motion. That is to be found in the statistical moments of the distribution. For example the root mean square velocity is quite large, the velocity of propagation of mechanical disturbances in the medium of the ensemble (velocity of sound). On the other hand, the average mean square <u>displacement</u> of any member of the ensemble, by the Einstein theory of Brownian motion, moves linearly quite slowly with time. That motion is a diffusion. In the case of equilibrium in the ensemble that motion is a 'random walk' diffusion. The results of high speed motion (essentially at the velocity of propagation) and high speed collisions (taking place at relaxation time intervals) is to create a random walk 'diffusion' that basically doesn't go very far. In fact the average displacement is zero.

Later on, it will be shown how that same random walk diffusion transforms to a mechanism for transport when gradients or rates of change are involved. Two basic reasons for interpolating this note is, one, that wave propagation and diffusion exhaust all local processes in dynamically changing systems - here they have already been shown to exist in equilibrium systems; and, two, diffusion is a lossy dissipative process which is associated with transformation of the ordering of energy from more organized to less organized form. It is thus intrinsically a thermodynamic process, exhibited intrinsically already at the thermostatic level of description.

As one final note, the measure kT (actually kT/2), it can be shown, is the measure of the energy which becomes equally partitioned among each degree of atomistic motional freedom. This is a remarkable result of statistical mechanics. It holds both for the displacement and the momentum (mass times displacement rate) degrees of freedom, when they are both easily accessible to coupled interaction. There will be more on this basic point later.

3. Equation of state; other thermostatic potentials - The atomistic conservations co-constrain the distribution functions to where the macroscopic ensemble measures corresponding to each conservation are determined, apparently independently. But the fact is that these macroscopic measures are also co-constrained. That resultant is known as the equation of state of the ensemble, the existence of a relation among the macroscopic measures of summationally invariant quantities. In the simple case the macroscopic measures are density ρ (associated with mass conservation), pressure p (associated with momentum conservation), and energy E (per unit volume) or T (these are associated with energy conservation). Commonly T is used as the macroscopic measure. Thus the assertion is that there exists a function f

$$f(\rho, p, T) = 0$$

Why?

The fact is that the equilibrium distribution functions were created by sustained fluctuations (and their equipartitioning dissipations) in the summational invariants. The method of exhaustive counting of these conservations indicates that these fluctuations, viewed again as a statistical process, are statistically independent and exhaustive.

So instead of examining a single fluctuation, one selects a minimum region in which near equilibrium processes can be said to take place (prior study has indicated that thermodynamic equilibrium, e.g., in the Navier-Stokes equations of hydrodynamics, is achieved at scales of the order of 10 mean free paths or relaxation times; that near equilibrium, e.g., in the Burnett equations of hydrodynamics or in Stokes-Einstein diffusion, is achieved at scales of the order of 3 mean free paths or relaxation times. These scales are not the elastic atomism scale of interaction but are augmented by the relaxation times for internal processes in the atomisms. More of that later). In that region, fluctuations related to individual fluctuations will take place. Since these fluctuations are linearly independent and exhaustive, one infers that

$$A' \, \delta m + B' \, \delta p + C' \, \delta e = 0$$

δm, δp, δe are the fluctuations of particle mass, momentum, and energy at the minimum atomistic near equilibrium box. These transform, at that level, into the minimum macroscopic measures.

$$A \, \delta\rho + B \, \delta p + C \, \delta T = 0$$

$\delta\rho$, δp, δT are the corresponding fluctuations of density, pressure, and temperature.

This expression, derived from the individual fluctuations, also represent the differentials of these macroscopic quantities. Ordinarily there are mathematical questions regarding integrating factors of such an equation before it can be integrated. The physical argument is that if a dynamic equilibrium exists (a bunch of sand particles in a container will not exhibit such a dynamic equilibrium unless sufficient potential is supplied at the walls. A vibrational energy in the wall will do, whereas temperature will not. A fluid stream, 'fluidizing' the sand, will create such an equilibrium), there must be a mathematical manifold for the system which is smooth enough that a local tangent surface - the condition for local integrability - exists. The physical fact is that the fluctuations making up the statistical distributions are large. Yet the existence of the mathematical manifold permits us to assume mathematical continuity down to the 'equilibrium' level of fluctuations. In the minimum box examined the number of particles may fluctuate, illustratively, from 0 to 10; similarly for the pressure, etc. The manifold is <u>not</u> smooth for <u>average</u> gradients or changes as great as 100% per mean free path or relaxation time, whereas it is for changes of 10%, almost up to 30%.

Thus the expression is integrable in principle. In practise the parameters, A, B, C, are not constants and require theoretical (kinetics) or empirical determination. Except for a few rudimentary examples, the kinetic arguments will not be pursued. (See, for examples, (7), (8).)

For example, in the near ideal gas case (near point particles that interact only by near elastic collisions)

$$A \ \alpha \ \frac{1}{\rho} \qquad -B \ \alpha \ \frac{1}{p} \qquad C \ \alpha \ \frac{1}{T}$$

so that

$$\frac{dp}{p} = \frac{d\rho}{\rho} + \frac{dT}{T}$$

For liquids and solids

$$\frac{d\rho}{\rho} = a dp \qquad a \approx a_o \left\{1 + bT\right\}$$

It is convenient to define other thermostatic potentials: entropy S, enthalpy H, free energy F, Gibbs free energy C, Landau potential Ψ, but it will not be necessary to pursue their derivations and the purposes they serve.

The one exception will be entropy. The essential law of physics - the first law of thermodynamics - is that energy can neither be created nor destroyed, at most only transformed. In a mechanical system, this would be expressed by

$$dE + dW = 0$$

Internal energy is reversibly transformable into mechanical work. In the simple fluid case, this becomes

$$dE + pdV = 0$$

using specific volume V rather than density or

$$dE - \frac{p}{\rho^2} d\rho = 0$$

in terms of density.

However (see (6)), it can be shown that if causality and determinism exist in mechanical systems, there must be a nonmechanical variable S, and a potential T, which represent an alternate form of energy change, that is

$$Tds = dE + dW$$

The quantity TdS represents the flow of heat. For systems removed from equilibrium, there is a production of entropy S associated with the dissipative process. Thus

$$T\Delta S > 0$$

expresses the dissipative nature of natural processes distinct from a universal homogeneous thermal 'death'. The conservation of energy in all forms, and the dissipative nature of all nonhomogeneous local process expresses the first and second laws of thermodynamics.

4. Equations of change - Given that a system is supported from outside by a uniform boundary potential, e.g., temperature, so that a thermodynamic equilibrium, described by thermostatic relations, is achieved, modest change in the ensemble can be defined by equations of change. 'Modest' will have the meaning assigned previously. If the atomistic relaxation time is τ_o, then the period P (or time constant) associated with the highest frequency time rate of change has to be greater than 10 relaxation times

$$P \geq 10\ \tau_o$$

and, similarly, the equivalent mean free path of atomistic collision δ_o has to be smaller than 1/10 the size of the field dimension D

$$D \geq 10\ \delta_o$$

The latter is meant to include the notion that the fractional magnitude of change of a thermodynamic variable cannot be as great as unity in a mean free path distance, but only 10%.

If these conditions are satisfied, the field is near equilibrium as demonstrated by the fact that locally the thermostatic relations still hold (with one exception), but as an added component of description it is then possible to prescribe uniquely equations representing the relations of change from region to region in the ensemble. The one exception in the ensemble field (that is of processes taking place in various regions of space throughout which the ensemble is distributed) is the case of shock waves.

A note on this process is in order. It turns out that the reason that the nonmechanical variable of heat flow had to be introduced (6) was to avoid shocks building up and losing mechanical determinacy. The introduction of entropy S and smoothing functions (diffusivities) which would prevent that loss of state by redistributing the energy, did provide an accounting scheme for all processes. The introduction of these transport mechanisms (diffusions) did not eliminate the possibility of shocks, it simply confined them to points, lines, and surfaces. Thus for rapidly changing fields, shock waves can build up but they are confined. Physics can treat them as 'jumps'. They are thin regions, 'surfaces', through which near equilibrium conditions do not hold. The fractional changes are too rapid. However, there are jump conditions involving the entropy which hold across the shock front. Thus in such extreme cases, the equations of change are not continuous, only piecewise continuous with changing boundary conditions at these 'jump' discontinuities. These may be overlooked at this point.

The equations of change represent relationships by which the local summational invariant changes from region to region. There are as many such equations as there are summational invariants. Thus for example, for the elementary fluid example, such relations would read like

$$\frac{D\rho}{Dt} = \ldots .$$

representing change of local density;

$$\rho\,\frac{D\bar{v}}{Dt} = \ldots .$$

representing change of local momentum;

$$\rho T \frac{Ds}{Dt} = \cdot \cdot \cdot \cdot$$

representing change of local energy.

The righthand terms, which only represent wave propagative terms or diffusive terms, are not specified here, only that they exist.

It should also be noted that the total derivative D/Dt is given by

$$\frac{D}{Dt} \equiv \frac{\partial}{\partial t} + \bar{v}\cdot\nabla$$

That is, D/Dt as an operator, represents two sorts of change - one, change with regard to time in a fixed local region, $\partial/\partial t$; two, a convective effect associated with existing gradients. The second term is the nonlinear convective term. It measures how much change takes place when a velocity field $\bar{v}$ sweeps across an existing gradient ∇.

5. Autonomous operation of the ensemble - These four descriptive measures furnish the essential physics for the autonomous functioning of a persistent ensemble which is capable of survival (sustained dynamic performance). The issue of autonomy deals with the question that the ensemble system need only confront boundary potentials which may be time invariant and the system can survive. When the potentials are not time invariant, the question always has to be examined as to whether that variation is responsible for running the system.

Examples of such one component systems are flow fields (of gas, of liquid). If the boundaries are a uniform pressure, or temperature, a dynamic equilibrium will emerge. If the boundaries are nonuniform pressure or temperature, a flow field will emerge. Yet, in the latter case, the field, locally, at every point will be near thermostatic equilibrium (except at shock interfaces, if they exist).

Thermodynamics of More than One Component System

Without going into details, if there is more than one component in the phase (e.g., gas, liquid, or solid), then a summational invariant exists for the conservation of each mass species. (If independent components are only transitory, there is no general need for a general thermodynamics of multicomponent systems, only some kinetics. But when change, including 'chemical' change, can result in the coexistence of more than one mass species, then an irreversible thermodynamics must be able to reflect the persistence of those processes.)

A prototype description for the field process was exhibited in a paper on osmosis (Appendix I in (7); also (8).)

In (7), it was shown that independent equations have to be written to express mass conservation of each mass species, and independent expressions have to be written for the dynamical equations of motion. The energy equation (i.e., how heat flux in the form of entropy change is distributed among various transport mechanisms) is unitary in tying together all of the transport conversions.

It is somewhat surprising that this clear decomposition, very necessary in the case of osmosis and other colligative processes, is seldom discussed or shown in any textbook sources.

The effect of expressing these equations independently is that, by taking sums and differences, the equations can be rearranged to one equation representation for a total or composite mean flux of the individual mass components, and a representation for the differential flux, the flux difference between components. The first expression resembles a one component equation of change for mechanistic motion. The second expression clearly presents diffusion (of one component relative to another). The potential which has the additive properties required to differentiate these processes is the chemical potential. In summation, it makes up the hydrostatic pressure; in difference it makes up the osmotic pressure.

But at the same time, chemical potential provides competence to deal with both chemically interacting or noninteracting streams. Thus a physical-chemical thermodynamics is very naturally introduced.

Thermodynamics of Complex Systems - Operation by Modes

There is a difference between complex systems and simple systems. It is in the nature of the response characteristics of the atomisms (6). In simple systems, when interacting collisions take place, the collisional interaction is quickly equipartitioned among the internal degrees of freedom of the atomisms. In statistical mechanics, it is shown that an internal energy of 1/2 kT is associated with each independent degree of displacement or momentum freedom. For example in a gas, a simple point-like molecule has three degrees of translational freedom so that its internal energy is 3/2 kT and its specific heat (energy absorbed per degree) is 3/2 k. A diatomic molecule adds two more degrees of vibrational freedom (one displacement, one momentum) for 5/2 kT energy. Clearly the internal energy has quickly equipartitioned.

But with complex systems, energy is not quickly equipartitioned within the atomism. Instead it is long time delayed and processed internally. There is no mystery in the system. The internal atomism is fluid-like; it is a fluid-like 'factory' that is conducting its own internal processes.

Yet the internal processes are still physical, and describable by a thermodynamics - if the ensemble system is persistent - because the system can only deal in the same external summational invariants, and the persistent atomisms have to obtain their supplies through the external (or translational) gates. What is new is that the natural time scale, because of the internal time delays, is no longer the relaxation time between collisions (or the space scale the mean free path between collisions). Instead, it is the internal day of the factory, that time over which the internal actions of the atomism are carried out.

The difference between simple and complex atomisms is that in simple atomisms the internal degrees of freedom basically act spring-like, almost nondissipative, whereas in complex atomisms, the internal degrees of freedom basically act fluid-like, exhibiting long delayed diffusivities as well as elastic characteristics. They are dissipative; there is an entropy charge for the maintenance of internal form.

In the case of complex systems, it is pointless to keep track of the dynamics in terms of collisional momentum as with simple atomisms. Instead, from the process of integrating the equations of mechanical motion for the long time scale of the internal factory day, the acceleration term (from mass times acceleration, the sine qua non of Newtonian mechanics, the inertial reaction) becomes vanishing small. Instead we find the energy dissipation, as the flux of power, distributed as a matrix of characteristic action modes for the atomistic species. Action is the product of energy and time. The action modes are the characteristic times and energies expended in activities required by the atomism for survival. They represent the matrix of activities by which the atomism budgets its energy in time. Survival is the maintenance of form and function by such an activity budget.

These action modes - characteristic of complex nonlinear dissipative thermodynamic systems - are like normal modes in a linear conservative mechanical system. They represent a matrix of limit cycle processes, of comparable energetics, through which the ensemble system can ring or circle through.

The ensemble systems are nonlinear because macroscopically they exhibit convection; they are dissipative because of the diffusions in both external and internal degrees of freedom. Their motion is sustained from outside potentials, e.g., temperature by radiation.

In a linear mechanical system, normal modes are the 'diagonalized' resultant of transforming a set like

$$m_1\ddot{x}_1 + k_{11}\,x_1 + k_{12}\,x_2 + \cdots + k_{1n}\,x_n = 0$$

$$m_2\ddot{x}_2 + k_{21}\,x_1 + k_{22}\,x_2 + \cdots + k_{2n}\,x_n = 0$$

$$\cdots$$

$$m_n\ddot{x}_n + k_{n1}x_1 + \cdots + k_{nn}x_n = 0$$

to

$$M_1\ddot{y}_1 + K_1y_1 = 0$$

$$\cdots$$

$$M_n\ddot{y}_n + K_ny_n = 0$$

As an illustration, in a double pendulum (one hung below the second), the normal modes are represented by the two pendula swinging in phase in the same direction (the low frequency normal mode), and out of phase in opposite directions (the high frequency mode). For any arbitrary start of displacements and velocities, the system will exhibit beats as it warbles between the two normal modes.

In a nonlinear dissipative system, of sufficient complexity to exhibit many action modes, we conjecture that there is a near diagonalization of modes very similar to normal modes. The conjecture is based on a demonstration within the hydrodynamic turbulent field process.

In nonlinear systems, the warbling is exhibited as a sharper switching among a ring of modes than linear beat phenomena. The factory day thus consists of action divided among these modes. These modes derive from the three types of field processes that can exist - diffusion, wave propagation, and convection. For such complex systems, their complexity arises from internal atomistic diffusivities.

A clue that such modal processes are not metaphors, but associated with physical mechanisms, and in fact can provide the basis of bridging the gap from physics to the life and social sciences, is contained in the following fundamental but rudimentary derivation.

The stress tensor E_{ij} represents the physical force per unit area that any portion of an ensemble exerts on the contiguous portion. (If x,y,z components of force are called x_1, x_2, x_3, or x_i components with $i = 1, 2, 3$, then E_{ij} is the specific force in the x_i direction on the x_j face of a small cube of material.) Since a stress system in neighborhood equilibrium cannot generate self-rotations - angular momentum being a summational invariant - the stress tensor must be symmetric. $E_{ij} = E_{ji}$. That condition provides equal and opposite force couples on adjacent faces of the cube which will prevent self-rotation, generation of angular momentum at a small scale.

In a mobile fluid-like medium, in which the atomisms are free to move about, the stress tensor will depend on gradients of velocity, and at most

- by Onsager's linear law - on such terms to the first order. The most general form of such a function - if electrically neutral - will be

$$E_{ij} = - p\ \delta_{ij} + a \left[\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right] + b\ \delta_{ij} \left[\frac{\partial v_1}{\partial x_1} + \frac{\partial v_2}{\partial x_2} + \frac{\partial v_3}{\partial x_3}\right]$$

There could be additional terms if electromagnetic and gravitational stresses were of any significance. This is a minimum and essential derivation. The term p is the hydrostatic pressure, the force that would exit if there were no motion. (The unit symmetric tensor $\delta_{ij} = 0, 1$ if $i \neq j$, $i = j$. That is, pressure p, is only a diagonal term appearing as a hydrostatic force). The symmetric velocity gradients are identified, assuming an isotropic medium, by two fluid constants, a, b. In conventional physical terms these are identified via the shear viscosity μ and bulk viscosity λ as

$$E_{ij} = - p\ \delta_{ij} + \mu \left[\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right] + \delta_{ij} \left[\lambda - \frac{\mu}{3}\right] \left[\frac{\partial v_1}{\partial x_1} + \frac{\partial v_2}{\partial x_2} + \frac{\partial v_3}{\partial x_3}\right]$$

But the equation for mass conservation is

$$\frac{D\rho}{Dt} = - \rho \left[\frac{\partial v_1}{\partial x_1} + \frac{\partial v_2}{\partial x_2} + \frac{\partial v_3}{\partial x_3}\right]$$

(Density changes by virtue of the divergence of velocity - its net flux - into the region.)

Thus

$$E_{ij} = - \left[p + (\lambda - \frac{\mu}{3}) \frac{D \ln \rho}{Dt}\right] \delta_{ij} + \mu \left[\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right]$$

Our interest turns to the ratio of viscosities λ/μ. The shear viscosity μ relates to the transfer of momentum from layer to layer of a moving fluid, time delayed by virtue of translational relaxation time. The bulk viscosity relates to transfer within <u>all other</u> degrees of freedom, that is transfer to internal degrees of freedom. The ratio λ/μ more specifically is the ratio of internal action to translational action (action is the product of energy and time). Thus

$$\frac{\lambda}{\mu} = \frac{E_{int}}{E_{tr}} \frac{\tau_{int}}{\tau_{tr}}$$

In complex systems, essentially the total internal energy comes from and is dissipated through the translational gate. Thus the ratio of energies is essentially unity. (As an illustration, essentially all of the energy absorbed by a living system, as food, is dissipated through the skin.) What remains,

$$\frac{\lambda}{\mu} \approx \frac{\tau_{int}}{\tau_{tr}}$$

is the ratio of the time delay internally to the translational time delay. The ratio λ/μ thus measures the internal day of the atomistic factory in translational time delay units. Since this is extremely large for complex systems, the velocity gradient terms in the stress tensor are vanishingly small. What remains is

$$\begin{aligned} E_{ij} &= - \left[p + \lambda \, D \frac{\ln\rho}{Dt} \right] \delta_{ij} \\ &= - P \, \delta_{ij} \end{aligned}$$

a hydrostatic-like pressure P that 'wells' up out of the interior actions of the complex atomisms.

That 'communal' pressure is a novel physical pressure. It is a third component to 'pressure'. Ordinarily the hydrostatic pressure is made up of the short range collisions in gases, as one component; in liquids there is the addition of a second component due to 'long range' forces (e.g., van der Waal forces) between molecules. Now, in complex atomisms - as complex at least as complex molecules - a third component wells up. This is the social pressure. It arises from those drives that maintain internal atomistic form and function within the atomism by action modes.

In a sense which may give the impression of being teleological, but is really not (it is more topological), the modes may be classified as aggress, defend, and maintain modes to indicate the 'direction' or orientation of the modal action (5, 9). Aggress modes involve self-initiated actions directed into the space of other atomisms so as to cause interaction; defend modes involve self-initiated counteractions directed against other atomisms who penetrate the surround space so as to cause interaction; maintain modes are self-initiated modes which are concerned with maintenance of form and function of the atomism.

In summary, in complex systems the summational invariants are mass, (or individual mass species if there is more than one component atomism), energy, and, instead of momentum, a distribution of action modes. Such physics is denoted as homeokinetic physics (6).

1. Equation of state - Given that atomisms assure their own form and functional persistence (by self-serving themselves from available potentials), the question can be raised whether any new concept is needed for the equation of state for complex atomisms? The answer is no. The equation of state still remains the linear statistical co-constrained association derived from the fluctuations associated with summational invariants. In the simplest case

$$a\delta m + \Sigma b_i \, \delta A_i + c\delta e = 0$$

there is an association among the fluctuations of mass m, energy e, and the individual modal actions A_i at the atomistic level. Summed over the local ensemble, this becomes

$$a\delta\rho + b\delta P + c\delta E \doteq 0$$

where ρ is the number density, P the social pressure (defined through the matrix of action modes), and E the specific energy, e.g., daily power dissipated by the ensemble.

Thermodynamics of Living Systems

Living systems add one more summational invariant, that of population number. Generation begets generation, a process which is insured by a carefully guarded genetic code, which acts as a particular chemical potential for the reproductive process.

In the simpler systems, thus far described, mass and number of atomisms were strictly proportional. Thus in any theoretical description involving fluctuation or change, one of these variables was a degenerate variable, rather than a new variable. In the living system, biomass and population number are not strictly proportional. The living atomism is a relaxation oscillator. Whether the scheme used is cellular fission or sexual reproduction, a growth process of material ingredients takes place, a division of matter, and continuing growth; also a death and dissolution of matter.

Such a distinction of mass and number is not unique to living systems. One has to consider such independent variables whenever a 'birth' and 'death' process takes place. Chemical change itself foreshadowed the need, in particular nuclear 'chemistry', in which matter is created and destroyed (it is matter-energy which is conserved in the physics of very high energetic processes, not the two independently). Thus any description of stellar dynamics includes such a distinction of process.

If a living ensemble system is to be viewed as near equilibrium, it is clear that the generation is the unit of time of the factory day, the internal relaxation time. And pursuing the transition from the kinetics of an individual event to the near equilibrium thermodynamics of the ensemble, it is more nearly three relaxation times, three generations, from whence near equilibrium arises. For a bacterium with a 'generation time' of the order of 20 minutes, this poses little problem in dealing with the issue for human observers. For a human with a 'generation time' of the order of 20-25 years, this is a problem. Near equilibrium is more like 70 years, the total lifetime of a modern individual. Not inconsequential is the ego of the individual who finds little foundation for dealing with problems beyond the 'here and now'. Yet we face that problem as soon as we turn to the physics of complex systems.

In a simple near ideal gas, as Maxwell showed, all transport coefficients (diffusivities) derive from a single relaxation time constant. However, by the level at which we reach, say, liquid complexity, we have to deal with a number of relaxation time scales, arrangeable as a sequence of inequalities, before ensemble near equilibrium time scale is reached. It is of interest to suggest the sequence of process scales which impact on the human, in a thermodynamic - statistical mechanical sense.

A. The "present" is a period of time lying between 2.3 and 12 seconds. (A conclusion drawn from psychological studies, related to brain function. Discussed in (9).) This is an atomistic perception.

B. Fragments of planned activity of the individual roughly coincide with a thermodynamic relaxation time in many body functions of the order of 3-4 hours.

C. The day is the unit in which most physiological functions of the individual are relaxed (also built into the brain, and tied to the night-day cycle). These become entrained, by resonance, into the ensemble, as a first level of considerable coherence.

D. There is a seasonal 30-60-90 day range to human activities. (While its causality is far from obvious, it finds weak expression in intellectual, emotional, outlook changes, and can be found, illustratively, in the scale of body weight regulation. Conjecturally, this scale relates to the turnover time of body constituents.) This is entrained as a seasonable component in living ensembles.

E. The yearly time scale is generally forced on the human via the earth's annual revolution and the engraving of that cycle within the ecological food chain. The internal apparatus of most living systems has cues drawn from parts or all of that cycle. In any effort to couple any living species into a symbiotic web, one must approach with great caution any mode of operation which disregards this time scale.

F. Finally, beyond the year, various natural scales of generation life arise, associated with the species, differing, say, for mice, maize, or man. While it is difficult for the species to hold a 'conscious' view of an entire generation time, one, clearly it is encoded within the organism, and two, few persons would deny that - whether they want to or not - planning for major life epochs has to be done. The issue is only the kind of memory function which has to be held for different types of activity.

In such a context then, the outlook sought will be one that should be good for "three generation" isolations, whatever the life scale whose generation is being focused on. It is not that initial concern in this program is with three generation human life, but that the operational principles, the thermodynamic guide, has to suit whatever mission is contemplated if the series of efforts is to have any ultimate use to this country. Ultimately, a program of this sort, if carried out, will have to address that equilibrium time scale.

1. Operation by modes - While modes derive from diffusive and wave propagative phenomena, when they appear as part of the complex of internal actions, due to large bulk to shear viscosity ratios in the ensemble, then it is necessary to determine the particular matrix of action modes that have been encoded within the atomism. In the case of living systems, these are encoded within the genetic code. Despite the more grandiose claims of sociobiology, it is not possible to dynamically 'read' the genetic code to determine what action modes will emerge from an organism. Instead the much more modest claim of ethologists is pertinent. By comparative study among various of the hierarchically arrayed phylogenetic orders, some notion of emergent behavior is possible. And at the more primitive levels, mutations suggest, to some extent, the sharpness of differentiation of behavior achieved by a few genetic changes (e.g., at levels of bacteria). The difficulty, with more complex organisms, like humans, who are not stimulus bound, is that complex behavior tends to follow more a 'law' of mass action. There is the suggestion that complex behavior tends to emerge from a great number of interlocking, to a considerable extent overlapping, genetic processes. In any case, the very first scientific step of going from the static chemical form of a gene (DNA) to its dynamic expression of function has still not been taken. Chemists and molecular biologists have simply not been willing to take seriously the complexity of the hydrodynamic transcription.

On the other hand, at the lower levels, there is a sense at which the modal processes are understood. Thus for example, a series-parallel characterization of modes in a simple bacterium (e.g., a ciliated bacterium) is essentially possible. It is contained in the action processes of ingest, excrete, grow, divide, move straight, tumble in motion. The genetic components that control these processes are coming into focus (10).

Making a far jump up to mammals, ethologists have classified their action modes into general categories (see (11)):

- ingestive behavior
- eliminative behavior
- sexual behavior
- care-giving behavior
- care-soliciting behavior
- agonistic (conflict) behavior
- allelomimetic (immitative) behavior
- shelter-seeking behavior
- investigatory behavior

Even if not a perfect classification, it does account for a great deal of mammalian activity modes.

From a somewhat different point of view (3) about 20 salient human modes were proposed:

- sleep (e.g., a sleep mode)
- work
- interpersonally attend (body, verbal, or sensory contact)
- eat
- talk
- attend (indifferent motor activity, involved sensory activity - here to non-persons)
- motor practise (run, walk, play)
- anxious (e.g., an anxiety mode)
- sex
- euphoric
- drink
- void
- anger
- escape (negligible motor and sensory input)
- laugh
- aggress
- fear, fight, flight
- envy
- greed
- rest (no motor activity, indifferent internal sensory activity)

(No apology is made for apparent poor grammar. Sleep - noun, to sleep - verb, anxiety - noun, to be anxious - reflexive verb, may be proper usages, but a sleep mode, an anxious mode, etc., portrays the state verbally.)

The general physical scheme is denoted as homeokinetic, by which a viable autonomous system (in this case the human) runs self-regulatory through all of its operational modes. In stimulus-bound organisms, a more rigid programming exists for these modes, which still leads to a successful (persisting) species. In the less stimulus-bound organisms, the human with internal abstract languages being the least bound organism, the ring of performance is basically more Markovian-like. (As examples, a night's sleep, after essential REM episodes, readies the organism, wherein either a cortisol signal or morning light are dual signals to wake the human organism and put it on the search for food. Plentiful food, particularly late in the day, tends to create a drowsiness. And so forth. Much of human behavior has that character, regardless of the great diversity of cultural differences.)

Why is there operation by modes? For linear conservative systems (like a collection of mass-springs) the modes are simply associated with degrees of mechanical freedom. For linear nonconservative systems, in which thermodynamic losses can take place, modes are associated with diffusive processes as well as propagative (elastic-like) processes. For nonlinear or nonconservative systems, the operational modes emerge from compensations which lock the system into limit cycle thermodynamic engine processes. They are thermodynamic because energy is transformable by both mechanical and nonmechanical means. They are engine processes because they are found in a sustained process cycle and they can do work. The modes are limit cycles because the cycles persist in the face of energy loss and they have some immunity to disturbances, and because mathematically, cycles are the only means by which persistent processes that preserve a formal character can be described. (The more precise mathematical statement is that a bounded function of limited variation can be described by a Fourier decomposition into harmonics.)

The clock is a simple example of a one mode nonlinear system. A clock is a time (or frequency) regulator. Its diffusional losses of energy, via friction, are made up by the potential stored in its escapement. What emerges is an apparent linear cycle. The continued oscillation of a pendulum in a gravity field (with an escapement) illustrates the process (e.g., a grandfather clock).

If, instead, such an engine system were run mainly to produce heat by its frictional loss, the observer would notice less its frequency regulation and pay more attention to its diffusive flux of heat (e.g., that phase in which a turbine is run so that it can produce heat directly by frictionally loading its mechanical output, which alternately can also run a refrigeration cycle).

In addition to such a 'hard wired' configuration, engine devices can be run so as to switch among more than one operating mode. That depends on the character of the coupling. Some such changes in coupling may change the 'wiring' in the system, changing it into different coupled configurations. It is such properties that the living system exploits in switching from mode to mode. As a very simple 'clocking' example, the regular heart beat of a mammal can occur from the autonomy of a leading segment of myocardial tissue to phase an ensemble of cells and spread an electrical signal over the heart, or - as an unwanted mode - the ensemble of cells can desynchronize with the heart going into fibrillation.

Whether stimulus bound or not, the organism goes through a series-parallel chain of such 'rewirings' in its modal operation. In the complex organism, the rewirings can be often recognized from the outside. Two illustrations which may help distinguish stimulus bound from nonstimulus bound responses of some great complexity may be useful.

If an animal is in an eating mode, most internal organ systems are coupled rather tightly. It is true, in humans, that some conversation, etc., can be coupled, but such off-diagonal coupling is not really great. It appears great in 'high civilization' because eating is much more ceremonious than physiological, there being a great surplus of food. (On the other hand, only rather large disturbances interfere with the coordination of a sex mode.)

Culturally, a human can be taught to dissemble. He or she may not exhibit external response to laugh provoking or anger provoking or anxiety provoking inputs. Nevertheless, there is little doubt that the basic physiological response is taking place. It is the outermost superficial responses which are suppressed or distorted. It has been the hope and expectation of biophysical programs conducted by the contractor, at some time, to be able to get at the internal physiological response. It is believed that these responses are to be largely viewed and examined in the endocrine and neuroendocrine streams, much less so in the neuroelectric streams. That is, the primary couplings, of a soft wired nature, in the complex human living system are fluid couplings of chemical streams.

It is at this level, basically of endocrine and neuroendocrine response levels, that the action modes of humans are formed. Thus, again, in process closure one has to have a sense of the near equilibrium time scales.

In earlier studies, it was shown that physical thermodynamic equilibrium in the human body took place with about a 3½ hour time constant. This agrees with the nominal time scale for relaxation of a food input. Whether these processes are intrinsically coupled (i.e., digestive cycle in the G.I. tract and the thermoregulation response of mammals at this scale due likely to cortisol) is not known.

Physiological thermodynamic near equilibrium in the mammal is much more tied to the day-night cycle. In that period, the human tends to run through most of his repertoire of action modes. The action modes are thus more commonly discharged in fractions of a day, e.g., like 90 minute REM episodes.

A description at this level can often be viewed as sufficient for the following reason: While the human is a relaxation oscillator with a start up life phase (say 0 to 20 years), and a degradation phase (say 60 years to death), the life phase - say 20-60 years - occupies most of the life of the individual. Thus its plateau-like appearance, and the memory span of the individual (for whom it commonly appears that 'one day is much like another'), makes near-equilibrium at the daily level the most common driving signal that individuals face. (And then on to the seasonal and yearly signals which are also engraved within biological organism function.)

But if concern is with the species, then the near equilibrium time has to be the generation time, for the human about 20 years, with three generation time 70 years being very close to social equilibrium.

With these numbers in mind, it is possible to move on to the equation of state for a living system - a species, or more specifically a breeding population in a species.

2. Equation of state - For a living system, the fluctuations that are coupled are individual mass species, individual action modes, the 'daily' energetics, and population number of a common breeding population (race). The graininess cannot be finer than 1 generation; but, conversely, one can integrate the statistical relation over generations to produce a near continuum distribution down to the three generation level. That process has been shown possible for the hydrodynamics of fluids.

However, there will be no great merit to highly abstract mathematical descriptions of such an equation of state. Its existence and the basic principles and details of the argument can be followed, descriptively, by partial budgets among the invariants when required.

The summational invariants are only the local conservations of energy flux, a matrix of modal actions characteristic of the species, a flux of various material species, and population number in the ensemble. The equation of state is an expression of how these variables, not for the individual, but for the ensemble, are related.

Thus, for example, without particularly elaborating at this point sharp distinctions between species which can photosynthesize energy and those that metabolize chemical free energy, among the latter it is typical that members of a family have similar specific metabolic fluxes. For mammals, Klieber (12) has argued that the rest metabolic power H varies approximately with the 3/4 power of mass of an average adult individual (M). Iberall (13,14), has shown a variation fairly close to the 4/5 power of mass, and a theoretical reason for that variation. (Blood flow and oxygen uptake are tied to proportionality by a common hemoglobin carrier. The blood flow has to uniformly perfuse all tissue. Thus design is tied to the characteristics of the arterial system, which has to be topologically similar in all members of the mammalian family with its common high pressure kidney system. Along two spatial axes, say x, y, the cost of that uniform perfusion is the viscous loss within terminal arterial levels; along a third axis, the height z, the cost is augmented by a gravitational head related to animal size. The combined processes scale the animal.)

In general, living systems seem to have low duty cycles, that is they operate on the average near the rest or idling state rather than at peak sustainable performance. The effort was also made in the earlier NASA studies to characterize the limiting aerobic performance for mammals. (For example, for humans, the rest metabolism associated with perhaps 1/4 - 1/3 ℓpm oxygen uptake or 1600 Kcal/day, can be raised tenfold to about 3 ℓpm or 25,000 Kcal/day, within the aerobic limit. Such levels are exhibited by marathon runners; they can very nearly be sustained for running periods as long as 24 hours. Athletic performance in the anerobic range, e.g., 3 - 5 ℓpm is possible for highly trained persons for limited periods of time. Related ranges of aerobic performance are possible for mammals of different sizes.) Characterizing the normal metabolic process is beset by a lesser degree of extensive data, although for humans it can be surmised that a 'normal' range may typically cover 2000 - 4000 Kcal/day as the actual duty cycle range. Further some studies have indicated the existence of a 'comfortable' range of activity for the organism. Such rate contrasts - 1600 Kcal/day rest, 2000 - 4000 Kcal/day normal, 6000 - 8000 Kcal/day comfortable sustained activity level, 25,000 Kcal/peak sustainable thermodynamic (aerobic) equilibrium - are indicative of the thermodynamic range of the individual (male) human organism.

When related to ensemble activity, one is confronted by the fact that at the highest rates life shortening may be a significant limiting factor, at the lowest rates pathologies associated with extreme sedentary efforts, e.g., obesity with overeating, starvation with undereating.

Thus, in an equation of state, metabolic rate is not only related to body mass, as a species specific characteristic, but it also related to the action matrix of the species, more particularly of the race. If a breeder, as a deus ex machina, puts environmental pressure on a species that he raises and harvests, that breeding ensemble has to respond from its species specific action repertoire - not only in the comfort pattern range that organisms may 'prefer', but in extreme survival patterns. We propose the following basic law: social pressure 'wells' forth from the interiors of an ensemble of complex atomisms to equilibrate the environmental pressure. If we view the external and internal pressure to have that character, it is not surprising that such pressure can affect breeding patterns. (The most horrible example of such deux ex machina performance was the Nazi's conduct of the concentration camps. Extreme examples of self-selected survival patterns are illustrated by human populations in the arctic regions, at high altitude, or in deserts.)

However, not only human breeders, but natural processes put the same kinds of pressure on breeding populations. One common difference between natural and man-sponsored breeding is that in nature there commonly is an opportunity for emigration and outbreeding, whereas human breeders tend to isolate the breeding population more, or try to exert high selection pressure to breed behavioral or physiological characteristics of both an epigenetic and genetic character. In thermodynamic terms, the natural process is more nearly isopotential (the generalized equivalent of isothermal calorimetry) rather than isolated or closed (the generalized equivalent of adiabatic calorimetry). One major difficulty arising from the latter type of breeding is that Man has little experience with long term breeding, as nature conducts the process. When a breeder has difficulty with a species or a habitat, he often rids himself of the race and gets another, or he moves on. In the conduct of his own breeding, Man has some consciousness of the poor consequences of inbreeding. All of these unpleasant considerations are involved in the equation of state of a living species in which the character of genetic reproduction, its reliability, and its responsiveness, are important factors in its persistence. All such issues have to be faced in closed systems.

3. <u>An interpolated note on the support potentials</u> - For a system to persist, whether at equilibrium or nonequilibrium, there must be support potentials. Potentials may be regarded as reservoirs which store energy and make that energy available upon suitable contact. The potentials which we have to be concerned with, in living systems, are a temperature potential, a radiation flux potential, chemical potentials for material species, and for free energy, mechanical pressure, gravitational potential, and electrical potentials. In addition, there is an onboard chemical potential stored in germ cells as the genetic potential. Higher species, Man, also possess an epigenetic value potential, which consists both of an extensive memory, and capability of transmitting that memory as a cultural heritage.

Given availability of materials and energy potentials, including rate governing limitations in mining or harvesting them, a breeding species must work out an action matrix which will satisfy survivorship, or it will not survive. That action matrix is costly in energetics; each activity having a power dissipation associated with it. (To illustrate such a gross pattern for human being currently: 8 hours sleep at a dissipation rate of about 1600 Kcal/day; 8 hours maintenance activities at a rate of about 2400 Kcal/day; 8 hours work at a rate of about 3000 Kcal/day. While there might be an inclination to regard such accounting as trivial, a national society and its leadership have to show some concern when 'suddenly' a particular new factor, television, intrudes and begins to occupy what is said to be an average of about 6 hours of daily viewing. That 6 hours largely comes out of maintenance activities.)

Of course an essential activity, even if impulsively (short interval) practised in time, is ingestion, that activity by which incoming power is balanced to the outgoing power of all other activities (including ingestion itself). In general, if materials and energy are rate limiting, it is activity and population density which are the variables manipulated by the species.

The net power expenditure - which is nearly equal to the intake power (the difference going to increase biomass of the species) - is expended to do external work, and dissipated through the avenues of net radiation power (positive or negative), conduction and convection power, and evaporative power. That portion is the standard balance of environmental physiology. In the equation of state, it is the total activity level and its disposition which is manipulatable by the breeding group.

We approach those aspects of the equation of state which have always posed paradoxical questions among people, and has led to such a deep sense that a descriptive science of living systems, most particularly human beings, is far different from nonliving systems. It will apparently deal with issues of 'volition'. Basically we will indicate that the question of 'volition' remains issues of stability branches (decision trees that are dynamically governed), and determined by some subtle consideration that heretofore have not been offered explicitly for these systems by physical argument.

Consider first nutrition. The usual sense of nutrition is that it is a supply, drawn from available potentials, of materials and free energies necessary for survival. We will pose the paradox that the purpose of nutrition is to make up for the members of the breeding group who have been 'harvested', either by natural death, predation, or by a deus ex machine.

The paradox is removed when a sharp distinction is made between the problem confronting survival for the atomistic individual, survival confronting the breeding groups, and survival confronting the species. Clearly all three 'atomisms' die, but at fantastically different time scales. The individual dies at the generation level, the breeding group disappears (by diffusion) in perhaps tens of generations, the species disappears in perhaps thousands of generations. The individual's ingestion is nearly balanced thermodynamically at perhaps the day. (In earlier NASA studies, we showed that thermodynamic heat balance occurs at perhaps the 3-4 hour level for mammals; the chemical thermodynamic balance occurs at perhaps the circadian day - most action modes, including rest, ingest, work, are discharged at that scale; a water compartment balance occurs at perhaps 3-4 days - we have inferred this from direct measurements and a great deal of environmental physiological stress information; however, there is a weaker and longer time balancing period - of the order of 30-60-90 days - over which a more total behavioral balance takes place. We have weak evidence that it involves emotional, intellectual, physiological processes seen, for example, in the period of balancing weight fluctuations. We have suggested, speculatively, that it is the approximate period associated with molecular turnover of proteins in the body, particularly in the CNS. Literally we believe it is a period for the thermodynamic balance of the total organism, in keeping the organism in balance with seasonal changes of the driven yearly processes of the earth. Beyond that period are genetic-epigenetic cues which lead to the generation and lifetime thermodynamics. Which, of course, then involves the second tier of issues.)

However, for the breeding group, the purpose of ingestion is to maintain the group. ("Eat, eat, my child, the children of country x are starving," is a common theme which many western children hear in their upbringing.)

The paradox which has to be removed here - it is not a thermodynamic paradox - is that the daily turnover, e.g., 2000 Kcal/day per person, does not all go to maintain mass and number of the group. Most of that energy is dissipative. It is exported daily. Only a small fraction goes to build biomass. This is not thermodynamically strange. For example in an ideal Carnot cycle, all of the energy which has been put in flux during the cycle cannot be converted to work, only a small fraction. In the living chemical thermodynamic system, input power is partitioned among work, heat dissipating activities, and building biomass. Thus the purpose of the group is to run the complex chemical thermodynamic engine process by which the group survives. It is certainly socially internal 'perfusion' processes conducted by every individual atomism by which the group factory engine process survives. It is that view which is necessary for a closed ecology system.

Thermodynamic considerations for a closed ecological system must take the generation time scale as its objective for the following reasons: First, it will not be possible to conduct such systems without some sort of ecological web (unless continued turnover emigration and immigration were permitted). Some of the elements of that web will involve generational issues. Second, as shown by Calhoun's mouse colony experiment (15), a quite carefully designed closed ecological mammalian 'paradise' did not result in an equilibrium continuation. After a period of Malthusian growth, the colony's population turned around and died out. The final generations became "lotus eaters," disinterested even in sex.

On the other hand, the point of view of preservation of the species does not have to be entertained. These closed ecological experiments, if and when they do involve long space voyages, are in fact the beginnings of broadcast emigration effects of a species, who will be sending out such breeding groups to test their capability of survivorship. This may sound like strange language in a late 20th Century government report. It is hardly novel in examining the written history of Man in any other era or place.

Therefore the study will take on the breeding group generational view for the equation of state. The reader will have to untangle it, whenever the need arises, and translate or transfer the problem to the individual.

Thus nutrition - materials and free energy - pass through the system. There are minimal requirements, and thereby rate governing possibilities, for the necessary potentials and the rates at which they can be taken up.

One senses a strong reason for niche formation in a given habitat. Given existing species (ecology) and the physical environment (geography, geology, climate), the potentials are prescribed. The species brings its characteristic action modes. These determine rates at which the potentials can be tapped and put into flux. Thus the breeding population basically runs its system as an open loop flow system. Recycling happens only by the long time accident of how its modes and machinery dictate. Thus in principle, in general, one has to learn how to conduct all of the nutritional material balances for the species before or as part of learning how to deal with recycling. As we will show, later, these are subtle sophisticated issues with regard to the human being.

Turning now to the population aspect, the basic population law for a homogeneous isolated breeding group is Malthusian

$$\frac{dN}{dt} = \left[b - d\right] N$$

N = population

b = birth rate

d = death rate

Predation, immigration, and emigration are excluded in this minimal presentation. Their existence is assumed when necessary.

At population equilibrium, $b = d$.

While the population law is valid - that is, it is the only valid statement which can be made about a homogeneous population, and, as we have argued, the only statement of the thermodynamic equilibrium is that $b - d$ must be severely bounded in time, i.e.,

$$\left[\int_{o}^{\tau} (b - d)\, dt\right] < \varepsilon$$

(this states that there exists a time τ, representative of a small number of generations, for which the net change in population has a zero limit) - the question or meaning of homogeneity has to be examined more carefully.

We have shown, by a simple geometric presentation of the argument, that the population law can be transformed into the following statement. The rate of change of population in an isolated breeding group, which involves both reproduction birth and death processes, is the difference between the choice function that the current generation elects to produce and the effective choice function for a lifetime ago, where the latter choice function is a suitable average over the form of the mortality law (e.g., Gompertzian).

But then reproductive species exhibit the following characteristics: They breed only during a particular age slot. The period prior to adolescent puberty is a period largely of growth. There is a reproductive age slot, associated with a fair constancy of body properties. Finally, while not perfectly coincidental with the end of the breeding age, there is a slow degradation in body characteristics to senescence.

As a result of this three phase characteristic, there is a difference between reproductive and fissioning species. A fissioning species more simply grows and divides. That may be described as a simple sawtooth relaxation oscillator. (There may or may not be death processes, only processes of stasis.)

Most natural reproductive species do not behave much differently. The growth period is loosely speaking 'linear' to puberty, reproduction, as a natural process, takes place in a relatively narrow time slot. That limitation occurs because natural death is generally governed by competing vicissitudes - 'predation' or 'harvesting' by macroorganisms, or microorganisms, species harvesting other species. The long life spans possible in laboratory designed isolation is not characteristic of life naturally, (e.g., 5 years that a rat's life may be stretched is not what it achieves on the average). That does not mean that a small fraction of long lived 'elders' who prove the existence of a long life span aren't found, only they essentially do not contribute to the statistics, nor are they needed except in small fractional concentration. One must surmise from such phenomena that the function of the long life span was to provide an ample design margin - for the precarious task of living against so much competition, to assure some command-control guidance to the young, to provide some selectivity in breeding stock.

Up to very recently, the same story was true for Man (see (16)). Up to a few hundred years ago, the average life expectancy was down nearly at the 30 year level, even though the life span was known to be up at about 90 years. Historical study and biological study simply indicates that living species have never sentimentalized about the old. Man today is the first species that does. (Note: The authors of this study are 'old'. It is no Lord of the Flies youthful arrogance contained in the observation. In studying history scientifically, e.g., examine Stone's The Family, Sex and Marriage in England, 1500 - 1800, we have to be impressed by the large amount of distortion of social priorities that took place with the human population explosion in the world after 1750. Whereas a small ruling elite could despotically dispose the little valued lives of subjects and followers prior to that age where, in common with all other species, the breeding of the young enough to overcome high childbirth mortality and reach breeding age was the major achievement, thenceforth the interests of a much larger older population began to dominate society. Does this process badly distort the natural inheritance of the younger adult whose major concern is and has to be with breeding? Such a question is peripheral to the subject of the thermodynamics of a closed ecological system; but nevertheless it is at that peripheral margin.)

Thus for species whose lives are protected past simple breeding to reproduce population (e.g., it may not only be Man in the system which is so protected, optimization of the utility of some other species in the ecological web of the system may also have to be so protected. For example a cow carried for breeding or for milk, rather than food, or a plant carried for seed, etc.), we find it necessary to distinguish at least three such life phases as youthful growth, mature life phase, and a degradation phase. Any 'homogeneous' population has to be made up of these three distinguishable states of atomisms. (This is not unusual in chemical thermodynamics, wherein both a variety of molecular states and some of their ionic constituents may independently coexist.) This poses no great problem. It requires some statement about that age specific distribution function of the species as well as number. This is certainly influential in characterizing the action mode spectrum which can be extracted from the ensemble. (For example, it may be desirable to distinguish these 3 average populations as an average youthful population characterized largely by growth of biomass and with negligible reproductive capability; a mature population characterized by little growth in individual biomass, but containing the reproductive slot of years, and exhibiting a broad range of action modes; an old population characterized by reduced action capability and negligible reproductive capability. The latter group are mostly consumers of available resources.)

Thus some general notion of an equation of state for the ensemble members of a living species has been provided and its connection with potentials. Given an environment endowed by potentials, over a few generations a major adult group of a species performs a variety of action modes, largely dissipative in character, sufficient to take aboard the required total energy (dissipative plus useful) and materials which will support both the newly growing biomass and the loss in biomass (due say to death), the required reproduction and nurturing activity of the young, the maintenance of the availability of required external potentials, and harvesting of these potentials (more generally these may be grouped as aggress, maintain, and defend modes), and choose the level of reproductive activity that will support near equilibrium. The fact is that the system runs near a dissipative border. However, it is the overcoming of these dissipations that is the requirement for thermodynamic survival. A youthful and an old segment of the population will be largely a cost to the race. The ingested energy is largely dissipated as heat; a little work is done on the external environment. There is a predation on other species and by other species. Finally there is a controlled immigration and emigration from other regions to the breeding group.

In defining a closed system, the implication is that the effort is to be made to curtail immigration (at least for the period of the experiment). This is a much more subtle process than it appears on first sight. But in any case this is a first round statement of the near equilibrium conditions appropriate to change in irreversible thermodynamics.

It would appear that a major function that this study has to succeed in performing is to set out and analyze problem areas and suggest where basic experimental studies are necessary. We start on that function in the next section. Up to this point, we have specified some of the essential physics of persistent ensembles.

PHASE I. - MAINTENANCE OF A BACTERIAL COLONY

The introduction just offered will have more substance when the problem of actual self-maintenance of a breeding group is discussed. For this purpose, a problem is selected from the bottom of the ecological chain. It involves living species, bacteria, whose presence will have to be assumed. In the main, they are the biodegrading mechanism by which chemical material can be returned to the chain. However, even their persistence requires the equivalent of a photosynthetic step from such a basic potential source as an absorbed flux of solar radiation. That is the only way that the chemical potentials required by the bacteria can be obtained in nature. Here an artificially maintained flow system will be described.

Consider the following flow system. It is offered as an extremely simple form of a constant potential system (i.e., the equivalent of an isothermal test system), here maintained by constant fluxes. Its design will make extremely clear what an equation of state involves for a living system, and why all four kinds of summational invariants have to basically be involved. We offer this system as a first test probe of theory. Not all scientists are willing to believe that there exists a thermodynamic systems science for living systems. So we have to demonstrate a constructive theory.

So imagine a U-tube with different heights in the influx arm and the outflux arm. Imagine a region in the influx arm which will constitute a field of observation. The net velocity in the field of view will be determined by the difference in height between influx arm and the outflux arm. Imagine this adjustable.

Permit a flux of thermostatted water to drip into the influx tube so as to maintain the level. Select a velocity that the bacteria to be observed can comfortably swim upstream against. (The bacteria to be chosen should be ciliated.)

Provide a constant concentration of materials essential for the makeup of the bacteria, plus chemical constituents whose breakdown will supply energy. This is achieved by adjusting the streams of these constituents, and making their supply proportional to the water flow.

We will make use of the action modalities of the bacteria as follows: We may assume that the action modes of ciliated bacteria are grow, divide, ingest, excrete, move in a straight line, tumble. In recent years it has been demonstrated that bacteria move longer straight path segments in favorable environments than in less favorable. These straight line motions are alternated with short segments of tumbling motion (the machinery has been traced to clockwise and counterclockwise rotations of cilia with a fairly clear grasp of the connection from specific genes to the control of energy activation to the actual rotational engine apparatus. It seems to be a clear case of a quite deterministic process.) The dynamics of the ensuing motion completely conforms to physical motions found in diffusion (8), namely, in a homogeneous medium, a general spherical diffusion will result (mean motion is zero, mean square motion is proportional to time); in an inhomogeneous medium, a plane diffusion will result in which the bacterial will move up a favorable gradient.

We propose to adjust our field to possess an essentially lumped character. That is, we supply such a dilute concentration of materials that the bacterial must keep moving toward the supply front to receive an ample supply, but we convect the field at a very slow rate. Thus the bacteria have to concentrate themselves in an axially short region where they can obtain nutrient to survive. If we supply enough nutrient, we can guarantee that more than one bacterium can survive.

Thus, we have made use of the motional action modes of the bacteria to keep them within the field of view. Clearly the action modes cannot be divorced from the materials flux and the energy flux being supplied via chemical potentials. And clearly we will depend on population growth by division and the modal operating conditions to develop and maintain an equilibrium population. Thus clearly an equation of state relation among these four invariants exists.

With all the potential and flux controls in place, now insert <u>one</u> bacterium into the field. It will grow and divide, etc. The question we raise is about the equilibrium. Let us note that there are four possible equilibria.

A. Suppose bacteria die. (If we conducted the experiment with some other species which do die, the situation would be quite clear.) The flow system was set up with a premise that facilitated diffusive motion was required to stay alive (moving in the field of view), and that dead bacteria would be swept downstream and flushed out. This is one particular harvesting scheme imposed on the bacteria, 'harvesting' by death. An equilibrium colony is developed. The function of the material supply is to make up for the constituents of the dead bacteria. The function of the energy supply is to provide the metabolic requirements of actively moving bacteria (not only their rest metabolism). The action modes are those, presumably of a low duty cycle, which the bacteria can perform 'comfortably' with long life.

B. Suppose bacteria go into a rest state, that is, they do not die. This is a strange resultant for the following reason. We may assume that bacteria only have sensors of their surround, as if it were homogeneous, rather than directional sensors. (Obviously higher forms have directional sensors.) Before the tumbling experiments, there always were conjectures that bacteria might respond to gradient differences associated with differential sensors from one point on their bodies and another. An entire scientific-philosophic revolution in thought suggests that it is local surrounding conditions that actuate responses (one may start from B. Goodwin's notion that temporal processes in cells (17) are their basic determinants, and that these are converted into spatial responses. We have suggested a similar physically derived theme both for cells (18) and even for human behavior (9)).

The tumbling experiments have clearly indicated that bacteria respond, by their actions, to favorable or less favorable conditions in their environment. We may similarly surmise that they have a response to noxious stimuli. It would seem clear, logically - if there is no directional sensitivity - that avoidance by moving 'away' from a noxious stimulus is not possible. (Only two motions - move, or tumble - are possible, and they provide the diffusion response to go from less favorable to more favorable environments, out of what is basically 'random' motion response, or actually indifferent responses). For noxious stimuli, the only possible motion would be either a high speed random motion, or overdrive, or a rest state. The latter response would be a chemotactic response.

In the field we have defined, chemotaxis could arise from neighboring bacteria ((19) is an illustration of such a response). In fact it is the only possible response, an indication from self and others, to cease motion or to change state. It seems clear that such a characteristic could emerge in a crowded environment, but there is no reason for such a signal to be produced in a dilute environment. The bacteria would have no way to distinguish between this field and a field that was extensively harvested (whether by death or deus ex machina). To insure that statement, we can imagine successively cutting the supply of nutrients in half, e.g., to support a sparser population. Thus there must be a lower limit in population in which the bacteria would have no reason to go into a rest state (e.g., as might be illustrated by contact inhibition), even if they did at higher density concentration. Since this is so paradoxical, we are forced to conceive of a third state. Thus, if the time to move becomes short, then even if they do not go into stasis, bacteria would be trapped in their toxic environment.

C. An oscillatory state. If there is a chemotactic response due to density (it cannot be in response to any other input - after all the environment is presumably designed to be 'paradisiacal'), then it is conceivable that as density rises, the chemotactic response drives the system to rest (assuming no cellular death) until the signal is adequately washed or diffused away, whence a cycle of growth ensues, until the signal returns, etc. The response might be imagined to be a sequence of monotonically rising undulations in density to a limiting 'carrying' capacity, given by the available flux of matter-energy divided by the average generation ingestion of matter-energy required to conduct the action modes of the species.

If on the other hand, death can ensue, then the oscillations would be around a constant value for which the peak density amplitude represented the level at which a 'poisonous' chemical signal was produced, and for which the lower limit of oscillation was at half density (that is, during each oscillation, nearly half the population would be wiped out and the other half would regrow to produce the toxic signal).

D. That there must be some merit to one or more of the three prior cases (among a variety of living species) is borne out by the 'more normal' situation of deus ex machina harvesting, where disappearance (natural death, predation, emigration, rather than the internal self destruction practised by the species) takes place with a minimum of interaction.

Examining Some Microbiological Literature

In reviewing the microbiological literature, there are three common limitations on their data. One common one is that the microbiologist practises his trade on batch processes and a point is reached in his experiments when he 'goes home'. The issues we are raising deal with what happens when he 'goes home'. A second, as in many fermentation processes, if a batch goes bad, the microbiologist throws it away and replaces it (e.g., commonly seasonally, when he takes the luck of the crop). The issues we are raising deal with what happens when you can't throw the batch away. A third case is that many drug companies, who may deal with harvesting issues, keep their findings as proprietary. Thus not all deus ex machina nurturing experience is necessarily widely available.

On the other hand there are two groups who do have a large amount of experience with continuous flow systems. One, microbiologists in the water pollution field are accustomed to deal with the stream problem in which specific sources of material-energy are discharged into the stream and they follow the course of BOD (biological oxygen demand) in the river downstream. "The stream purifies itself," is their original dogma. In fact it is in good part our experience with this group which has helped furnish us part of our experience and knowledge base behind this study.

The positive results we are aware of is that almost regardless of the nature of the organic input, there is a two exponential drop and recovery of oxygen concentration in the river indicating a linear concentration oxidation process going on, starting with limiting density near the input, and spread through the river length with a specific kinetic scale. Also there is a production of dead bacteria. Thus the cases we have enumerated, in part, reflect this experience.

The disadvantage to their findings is that they are not conducted with a pure strain of bacteria, but a mixed strain. Thus the bacteria themselves optimize (and apparently damp any possibility of oscillations) the relative growth processes among strains. Also the laboratory experiments these microbiologists do in order to derive kinetic constants for different inputs are done in batch processes (generally for the first increasing phase of growth).

With this introduction, we can start at the task of indicating what might be gleaned from microbiological literature about the task of characterizing a microbiological equation of state.

Population Growth

A rudimentary law of growth for bacteria is given as a van't Hoff-Arrhenius type reaction rate. That is, the basic assumption is that the growth in population number is itself a measure of a single equivalent rate governing chemical reaction. Thus

$$K_{T_2} = K_{T_1} \exp \frac{\mu}{2} \frac{T_1 - T_2}{T_1 T_2}$$

relates the reaction rate constant K at two temperatures. A common measure used Q_{10} is the ratio of the reaction rate at a standard temperature plus 10°C to that at the standard temperature

$$Q_{10} = \frac{K_{T_o + 10}}{K_{T_o}} = \exp \frac{\mu}{2} \frac{10}{T_o (T_o + 10)} \approx \exp \frac{5\mu_o}{T_o^2}$$

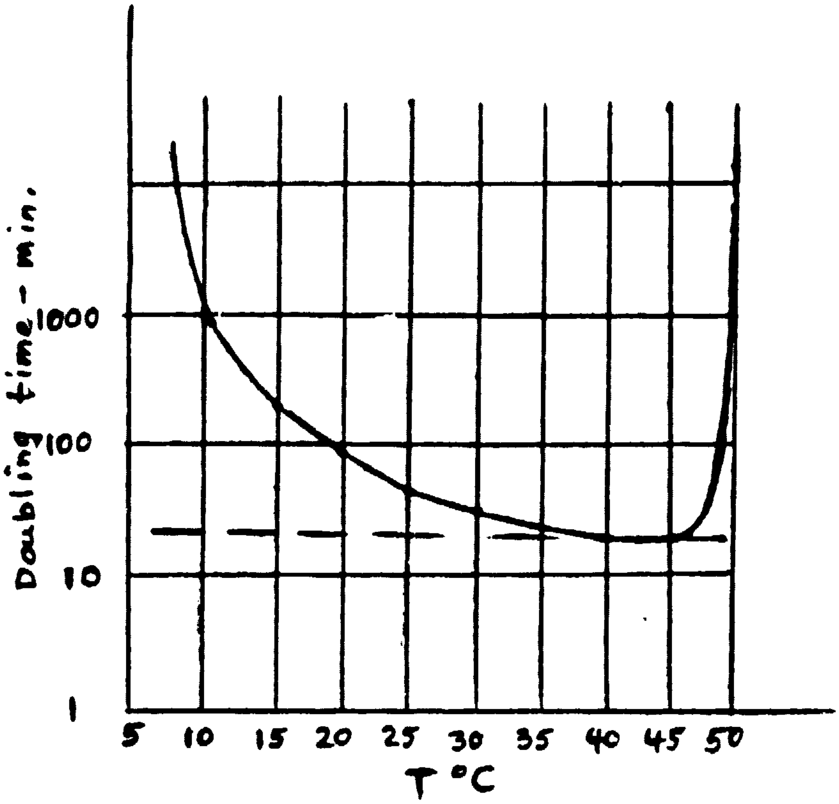
Typically, the temperature coefficient Q_{10} is about 1.3-3 (median 2.2, average deviation ≈ ± 0.4) for a variety of life functions for cells and organs. It may have such a flat coefficient for a temperature range of about 15°C.

E. Coli is commonly used as a typical example of bacterial response (20).

Multiplication of e. coli (20)

Temperature °C	Doubling Time min	Q_{10} for the interval
5.0	∞	∞
10.0	865	20.5
15.6	161	3.7
19.5	95.6	4.2
25.5	40.3	2.1
30.5	27.5	1.6
35.0	22.0	1.6
40.5	17.2	0.6
45.2	20.0	0
50.0		

Examining the doubling time carefully (figure below), e. coli - as a typical bacterial example - operate at an asymptotic regulated linear level of 20 minutes doubling time over a narrow range (35 - 46°). When temperature drops as low as 20°C, or as high as 48°C, their division process becomes very sluggish (e.g., 100 minute doubling time).



Data on another bacterium, bacillus ramos, a large bacillus, show similar characteristics for Q_{10}, except that the division process becomes very sluggish at about 10 and 30°C, and has a flat doubling time over the range 17 - 27°C.

The living system generally is found operating in a temperature range in which one can note perhaps five distinct points - a point for death in the cold, a minimum life temperature, an optimum temperature, a maximum temperature, and a point for death in the heat. Most commonly death at high temperature is caused by the heat inactivation of some protein. The temperature coefficients for the coagulation of proteins or heat inactivation of a toxin or enzyme is high. It may range from 7 to 700. (Heat inactivation of botulo-toxin = 7.4, heat coagulation of egg albumin = 646).

Cellular life will tend to die from heat at a temperature at which some vital protein coagulates completely. Below that temperature coagulation is a slow process (because of the large temperature coefficient). Typically the production rate - of protein or enzyme - will be greater than the inactivation or destruction rate below that coagulation temperature so that the inactivation is hardly noticeable.

In fact, it is quite likely that there is a median temperature (or range) in which the production rates will so exceed the damaging or inactivation rates that an optimal temperature range for that form will be found.

At low temperature, the cause of death is not so clearly marked. While one might regard the normal freezing of water (0°C.) to represent a dangerous threshhold, it is not universal. The 'shock' of high cooling rate often is a more severe variable. Internal water is so carefully shielded that it may be supercooled many degrees without fatality. On the other hand, tropical plants and tropical fishes will die if exposed to moderately low temperature for some length of time.

It is apparent that transport coefficients (viscosity, diffusivity) associated with protoplasm and lipid constituents of membrane are affected by temperature. These are assumed to have an effect on life processes. A common assumption is that harmful metabolic processes are eliminated or oxidized much more slowly at low temperature.

Existence of a Large Reaction Complex

Thus, although the doubling time - temperature curve is U-shaped with a flat asymptotic bottom range of preference, indicating a similar reciprocal (inverse-U) property for a single equivalent reaction rate of association of biochemical product, that life midrange does not consist of a single or even a few coupled reactions but a large complex of reactions even in the simple single cell organism. Internally the organism is a factory. Yet the U-shaped curve for a given species, and its ubiquity for many species indicates a large degree of systems' commonality in all living cells. (This is not meant to be any absolute surprise. After all the acqueous chemistry is very similar and operates with similar energetic exchange levels.) A large degree of cooperative phenomena is implied. The barrier limitations imposed by the temperature 'walls' apparently emerge from a small number of limiting physical-chemical mechanisms, i.e., chemical or physical transitions, or differential reaction rates. If one takes note of the central thesis of the geneticist, that survivorship of number is the major measure of success in a biological species, then this one dimensional cut in behavior with regard to a major environmental potential (temperature) assumes its significance. Life, in the end, is the autonomous persistence of an ensemble of coupled chemical reactions in a multidimensional space whose dimensions are largely the external potentials that are available to the system (i.e., its homeostatic or homeokinetic definition).

While the 'metabolic' activity (e.g., the reciprocal of the U-shaped doubling curve) is nearly a single flat arch between temperature limits, in the case of multicellular animals, say particularly thermoregulating mammals, there is more nearly a series of arches of different metabolic heights and shifted temperature range as the animal permits its nervous system to select an activity level. This may range from sedentary rest (e.g., 1/3 ℓpm O_2 uptake in men); to moderate activity (1 ℓpm O_2 uptake); to limiting aerobic metabolic activity (3 ℓpm O_2 uptake). This illustrates a considerable range of nonstimulus bound activity, differing from stimulus bound animals. (An interesting addition to activity range in vertebrates to supplement (13) may be found in (21).) Nevertheless, even in mammals, there are preferred levels of activity with temperature that will only reach sustained extremes for parameters not related to temperature. Such animals literally do have a broader parametric model for behavior.

To introduce another facet of difference between the unicellular and the multicellular organism, consider mortality experience with time for a single cell and a multicellular organism when faced with a lethal input.

The single cell organism will commonly display a logarithmic mortality decay linear with time

$$N = N_o \, e^{-\lambda t}$$

On the other hand, the multicellular organism will display a time delay t_o of appreciable magnitude before an essentially logarithmic decay

$$N = N_o \, e^{-\lambda(t-t_o)} \, , \quad t > t_o$$

takes place.

Rahn has attributed this delay to the equivalent of requiring mortality in multiple numbers of cells, e.g., "if the death of more than 10 cells is required to kill the organism, the calculated death curve agrees with the observed order of higher organisms."

With regard to the behavior of microorganisms, we can turn toward a 1970 symposium (22), which states that "in 1906, H.S. Jennings published his masterful book, 'Behavior of the Lower Organisms'.... Since that time no book has appeared on that subject. {This symposium was}...invited...on behalf of the 10th International Congress of Microbiology...the first opportunity since 1906 to bring together...the progress in this area...." However, there is at least one book in that intervening time frame, not mentioned, by Fraenkel and Gunn (23).

To provide a general definition from these two sources, taxis is the response to stimuli (e.g., chemical) by active movement among mobile microorganisms; tropisms are growth movements by sessile species.

However, to avoid reviewing apparently 'dated' material, we will combine information from that reference with material from (24).

A suitable keynote is taken from a review article on swarming of the bacterium Proteus, concluding with the 1949 review statement of J Krittingen, "In the course of the time this work on the life-cycle of... has been going on, and as new details have been clarified, the feeling has increased that the full understanding of the biology and sociology of the microbe becomes increasingly evasive." We take this note - generalized beyond the specific example it referred to - to mean that while a physical reductionism may only have a limited number of forces and forms available for the exercise of these forces, say at the atom - ion - molecule level, association of systems' actions possible even at the microbial level has already become so rich that it is only detailed experimental observation that can provide an efficient tactic for determining the full range of behavior (action modes) emergent from the physical-chemical apparatus. The classification of physical-chemical processes and forms can only be after that fact. None of this contradicts reductionism, only defers its efficient role.

Motor Actions

In (24), Canale-Parola ("Mobility of Spirochetes") cites that "in recent years considerable progress has been achieved in describing and interpreting the mobility of flagellated bacteria. It has been demonstrated that bacteria such as Escherichia coli swim in smooth, almost straight lines or runs interrupted by jiggling motions...called twiddles or tumbles, after which a new run starts in a randomly chosen directon.... The bacterial cells are propelled by rotating, helical flagella, each driven by a reversible rotary motor at its point of attachment to the cell.... During smooth swimming the...flagella...function as a coordinated helical bundle that pushes and rotates the cell.... When the direction of flagellar rotation is reversed, the direction of swimming is altered, e.g., a tumble occurs.... Furthermore, the frequency of tumbles is modulated in concentration gradients of chemoattractants or chemorepellents...." But, "in contrast to the relatively broad picture that has emerged from studies on flagellated bacteria, our knowledge of the mobility of spirochetes is meager and fragmentary." In (22), Dryl indicates a rather complex and incomplete chemotaxis in ciliate protozoa (in part a so-called "avoiding reaction"). He calls attention to more detailed classifications of elementary reactions in Fraenkel and Gunn (23).

Fraenkel and Gunn state that classification of animal orientation reactions are due to Loeb (1893), Mast (1911), Kühn (1919), Gunn (1937). All of these refer to motor responses which guide the animal into behavior which is of importance to maintaining the life process. First there is a primary orientation, a basic balanced posture of the animal. Then there are secondary 'orientations', directed reactions involving locomotion (or motor activity), which serve various functions. Originally taxes were identified to distinguish reactions of freely moving organisms from tropisms, reactions of sedentary plants (physically an objectionable distinction, since there are motions in both systems), but generally tropism has been dropped and replaced by taxis, to denote directed orientation reactions, e.g., toward or away from or transverse to the stimulus. Kineses are undirected locomotory reactions, in which the speed of movement depends on the intensity of stimulation. Major examples are orthokinesis - variation in forward velocity depending on stimulus intensity (leading for example, to aggregation); klinokinesis - turning frequency depending on intensity of stimulus. Among the taxis, they discuss klinotaxis (wavy motions), tropotaxis (straight motions), telotaxis (motions that do not depend on summing stimuli, but responding individually), light compass reactions, circus movements, photo and skototaxis (light or dark orientation), temperature orientations, gravity orientations, geotaxis, mechanical stimulus orientation (e.g., contact, sound), chemical stimulus.

Having examined the complexity of responses shown in the animal kingdom by Fraenkel and Gunn (23), and by Wilson (25), there is no great surprise, only detailed expositions in the articles in (22) by Adler (chemotaxis in e. coli); Dryl (chemotaxis in ciliated protozon); Miller (chemotaxis in animal spermatozoa); Konijn (chemotaxis and aggregation in slime molds); Mascarenhas (pollen tube chemotropism); Nultsch (phototaxis and photokinesis in bacteria and blue-gree algae); Diehn and Tollin (photo-taxis in euglena); Allen and Haberey (amoeboid movement and behavior); Bruce (phototactic clock rhythms in microorganisms); Hastings (rhythms in dinoflagellates); Woodward and Sargent (circadian rhythms in neurospora). Other papers deal with physiological mechanisms. There is one interesting paper (Davenport) on a rather complete observation and data processing system which "can in effect put a small aquarium a few millimeters squre on the stage and focus up into it either with low power or with a long-focus, high dry lens."

However, as (23) points out, all behavior is not mechanistically fixed. They point out, as sources of variation, first statistical distribution, which, if well ordered, would be scientifically overriding whether a claim for 'free will' would or could not be made for the individual (e.g., prediction of human birth rates). Second, the combination of operative mechanisms may create occasionally unusual individuals, but combinations of such 'normal' factors do not require exceptional or higher modes of behavioral explanations. On the other hand, there may be different homogeneous groups of animals (e.g., a bi-modal distribution of photopositive and negative responses of some larvae species of barnacles). Some animals react differently to different stimulus intensity (e.g., euglenia is photopositive in weak light, negative in strong light). Another behavioral factor may be age (physiological mechanisms in fact may differ; e.g., newly hatched blow-fly maggot is positive to weak light, and soon becomes negative).

These are all more easily understood physically. Difficulties start with the issues that are more 'historical' and 'evolutionary'. Beside immediate effects on behavior, stimuli also invoke delayed effects; repeated stimuli invoke modified effects. These responses raise questons of processes and mechanisms for memory, habituation, learning, adaption, transmitted adaption, evolution. In (23), it is pointed out that "modification in behavior due to experience takes place even in Amoeba." In other cases (e.g., snail exposed to light), the animal can become habituated to a stimulus. While some reaction patterns are inherited (and genetically encoded) in each species, some or all may be modified by experience.

In (22), Applenhite points out that "the first thing to establish in studies on the molecular basis of memory, is that the organisms chosen do, in fact, exhibit learning." He points to the limited definition of habituation, as part of learning, a "waning of a response as a result of repeated stimulation," using the example of habituation to an addictive narcotic as an "immunological memory"; it is not a model system for learning. In studying habituation in a protozoa to a mechanical stimulus, he shows that the site of the change is not local by demonstrating habituation in two cut pieces. Study of the response behavior in both species and flatworms, finally leads him to the conclusion that "habituation behavior is virtually identical in a protozoan and a metazoan and such behavior is not an isolated event in the animal kingdom."

He examines (but not necessarily convincingly) whether de novo macromolecular synthesis seems necessary for habituation by performing habituation experiments over the temperature range 5 - 32°C, finding the habituation rate independent of temperature, although the Q_{10} range would be large. From this he infers no synthesis taking place, or at least no synthesis requiring energetics. Yet in recovery to pre-stimulus levels, that behavior is temperature sensitive. Some energetic process might be taking place then. But he can only detect RNA increase. "Any protein increase may be just too small to detect in the organism." (In the Llinas-Iberall model (18), we would regard memory to be localized in the formation or disappearance of new membrane channels, a turnover process that might require only an insignificant portion of cellular energetics.)

He makes the suggestion that an alternative to protein synthesis for habituation is ion flow, but he could detect no changes of Na, K, Mg, N, Ca across the protozoan pellicle nor exchange with the surround. He infers that habituation must deal with an internal system. (Llinas has been very prominent in exposition about the nature of Ca, and Ca channels in nerve processes. Thus this kind of specific biochemical work, directed at identifying the biochemical 'sources' or concomitants of behavior is valid but in an extremely early and primitive stage. These examinations simply confirm that. Thus behavior and biochemistry must still be largely examined empirically.)

To cite some very current notions about behavior, we can refer to a recent review article by Quinn and Gould (26). They examine what can be learned from single gene mutations, acting at the "ultimate common denominator of behavior - the physiology nerve cells and the wiring patterns of neural circuits." They discuss results in terms of the underlying ionic mechanism for neural activity, e.g., Na, K, Ca. They examine results in unicellular organisms - Paramecium ("although unicellular, Paramecium behaves as if it were rational"); in multicellular animals - Drosophila with 10^5 neurones; in crickets; in nematodes ("behavior of multicellular animals is the result of interactions between nerves. Conceptually...two parts: how nerve circuits work, and how these circuits came to be appropriately wired during development....The most ambitious attack on the genetic control of neural wiring is...with the nematode C. elegans... creature has 'good' genetics, compensatingly simple taxis behavior, and a seductively finite 258 nerve cells.... Four parts: the head {50 or so nerves}, which contains virtually all the sensory apparatus; the pharynx, which mediates ingestion {20 nerves - sensory, interneurones, motor neurones, and multifunctional cells acting as both mechanoreceptors and motor neurones. These have been sorted into a plausible circuit of action pattern units (26)}, a nerve ring {200 or so nerves that make up a complex maze for sensory nerves and interneurones}. The muscle system can be {similarly} classified: the head muscles, which aim the head; the pharynx muscles, which manipulate and pump food; the neck muscles, which help aim the head and aid in swimming; and the rest of the body, which swims"); and in mouse mutants ("mouse brains...are organized like ours.... Large areas...such as the cerebellum and visual striate cortex...are composed of similar circuit elements.... So far, in spite of...elegant analyses, the mouse mutants have taught us little about the development of the cerebellum and nothing about its functions"). While these studies relating genetic and neurophysiological mechanisms are still quite primitive, work of Llinas' group, with whom we have been associated, on development and signal processing in dendritic trees, has reached a stage where an exciting new point about cerebellar processing is soon forthcoming (28). It is a proposed generalization analogous to Einstein's theory of general relativity, the laws of physics are independent of the coordinate system of the observer. Basically it asserts that the coordination provided by the cerebellar portion of the nervous system is independent of the network parameters, and dependent solely on time characteristics of the input signal. This is a new vantage point beyond that reached by McCulloch (29) in such questions as formal neuron properties, or the neural logic of universals. While apparently restricted to the motor axis of behavior, the notions will receive further generalization for both sensory and internal nervous system processing.

Beyond such neurophysiological study, there is the reach toward some broader 'ethological' themes. It is not only the case that behavior is modal, as surmised by Iberall and McCulloch (3, 9), and as borne out for mammals by ethnological study, e.g., see Scott in Havez (11). Instead there is: (a) an organized sweep to behavior (30); (b) in the 'choreography' of movement and its 'language' (see for example, Golani (31)) among members of a species; (c) a richness of interaction among socially bound individuals (see for example such still primitive studies as (25) and Thonon, et al. (32)). There is a very rich orchestration of behavior. (This is very evident in human beings where it has transformed from Paleolithic hunter-gatherer human societies to the richness of cultural-ethnic forms that modern history has demonstrated in ecological niches all over the world, except for the exclusion of extremely severe Arctic regions (32).) A very subtle form of explanation of the physical nature of space - time - niche bonding is attempted in one particular study by an explanation of how two species avoid competition for what appears to be the same energetic resources by their orchestrated action modes (33). It seems quite clear that the thesis of our colleague, Llinas (28), of the tensor transformation nature of the living organisms' command-control system in determining behavior may develop in time to be a major theme in understanding or orchestrating a long term ecological system. (At the present, the theme is still only provocative and not yet fully convincing.)

One further complication in behavioral processes in organisms, including microorganisms, is the existence of biological clocking mechanisms covering a large range of frequencies or periods. Some of these processes and mechanisms are described in (22).

We can only conclude that long term organismic behavior, as far as its equation of state is concerned, is at least as complex as that for the plastic-elastic solid state. (The plastic-elastic solid state is only regarded as simple by those who do not have extensive experience with such material under stress.) This means that there are short and long term internal spectroscopic (periodic or loosely periodic) processes; thixotropy, habituation and learning (processes that depend on previous history and a memory function); aging processes; and a change in genetic coding. Yet these changes are not so marked or so rapid that it is impossible to track the system. It means that the system can diffuse or trace a much fuzzier path of uncertainty than simple physical systems (which are bound very narrowly by Heisenberg's uncertainty principle).

Since the basic coding for social pressure is internal, genetic (also epigenetic among humans), in response to environmental pressure, in order to prevent unsatisfactory drift of the species, a physical strategy must be adopted for this program. In the end, it likely has to be the same one that human beings use on earth. In order to prevent breeding or racial drift, it is desirable that occasionally some remixing with parent stock take place. It appears that drift is particularly significant in small isolated population. Thus a significant part of such space experiments likely requires testing of three strategies: no mixing, a small amount of remixing of current earth stock, and considerable remixing. At present, we cannot suggest the best time scale for such mixing. A limited time scale (10 years to a few human generations) may not put any severe pressure on human breeding stock; it may on microorganisms. Thus it is certainly the more rapid breeding stock of lower life forms for which the major concern is being shown. These issues are worth exploring in earth based and space based experiments.

The second design principle which these themes suggest is that the design of an optimal ecological web must be carefully tested. In fact more than one web may have to be tested, on earth, before its suitability for isolation can be known. The issue will be even more severe when the range of health and disease are considered.

Materials, Energetics

The utilization and turnover of materials and energy by the living system begins at the level of macromolecular processing in the atomistic cell. Many of the processes in the multicellular organism still represent an orchestration of unitary processes in the single cell. The prokaryotic cellular processes, such as in E. coli, are suitable indicators of the more primitive forms of such processes.

The following may offer some rudimentary notion of temporal processing in cells. We will simply offer macromolecular synthesis as a single example measure. RNA polymerase in E. coli can covalently join 30 - 40 nucleotides per second. However, by the time the composite action of vibrational, transfer, and messenger RNA syntheses is considered, a broad and variable range of processes are found. Typical induction curves for a bacterial enzyme may consist of a lag time of the order of 3 minutes, and a linear induction period from about 3 to 12 minutes. Such processes lie within the cellular doubling time of about 20 minutes.

A comparable process in a mammalian cell, with a typical doubling time - for cells that grow and multiply - of perhaps 24 hours, might represent a lag time of the order of 3 hours, and a linear induction from about 3 to 8 hours (34, 35, 36).

We note the comment in (36) that "in conclusion, it can be said that the kinetic analysis of macromolecular events in eukaryotes is just beginning. It will be a critical area to develop. The {available} estimates of rates of syntheses and decay...come from the rather limited sets of examples available."

In any case we are left with a sense of fittedness. In a bacterium, the internal chemistry suggests that one may not view near equilibrium processes in less than minutes, and the simplicity of the complex of <u>all</u> the chemical processes puts the primary time constant at ≈ one generation of perhaps 20 minutes. Thus the simpler life forms have the character of ensembles of gas molecules wherein all transport processes - for materials, momenta, and energy - elaborate from basically one relaxation time scale (and mean free path of spatial motion). On the other hand, the more complex mammalian forms (of which the human being is sufficiently typical) are dominated by a greater complex of physical chemical processes. Yet enzymatic protein induction times of 3 - 8 hours are suggestive of why coordinated activity complexes of the order of 4 hours may be a common near equilibrium time scaling in animals (for example, it is a time scale that we established for thermodynamic equilibrium of thermal processes) but that a large amount of chemical thermodynamic near equilibrium is established at a circadian time scale of 24 earth hours.

Conclusions

While a fair amount of material has been brought together regarding, say, maintenance of a bacterial colony from a physical point of view, as one example of a living system, it is not strikingly conclusive. It suggests considerable merit to experimental study and to paying very close attention to how actual living systems, e.g., bacterial forms, really survive. The task of closure even in a microbiological domain which has to be depended upon to produce reliable harvest is one that deserves considerable experimental study. We recommend such study in the form of flow processes.

For this first review, this point is as far as we might go. So we jump very far now.

PHASE IV. EQUATION OF STATE FOR A HUMAN COMPONENT

The same four summational invariant variables govern the human being - energy, action modes, materials, population number. For closed systems involving time scales less than a generation, reproduction is not a pertinent variable. On the other hand, the very political nature of such human social missions as exploratory colonies in the 'new lands' of outer space puts a high premium on success, so that the existing population has to be very carefully shielded, by experimental design, from death or serious debilitation. For long missions, this is very difficult and it puts forth one more illustration that minimal webs have to be optimized not only for minimal survival but for both health and disease.

We have not completely discussed the required potentials for human operation. They are, loosely speaking, 5 potentials - a temperature potential (a requirement common to all living systems); a free energy potential (for photosynthetic species, these are minimal; for other species, the free energy potential has to be drawn from an ecological web and earth potentials - this may be loosely identified as ecological - geographic factors on earth. In a closed system, it is the design at the equivalent of an ecological - geographic milieu which is the problem); a genetic potential (possessed by each species as a carefully protected chemical encoding whereby species member is reproduced by species member); an epigenetic potential (restricted almost completely to Man, it is the learned heritage which is passed from generation to generation. It is the heritage of culture. In any closed ecological system, that background of culture is the dominant potential which provides the system with its particular dynamic patterning, or 'color'); the technological potential (we have defined this as the rate of change of the technological aspects of the epigenetic heritage whereby power applied to the environment by Man's action modalities is increased, or the action modes themselves modified. We regard it as essentially linear over the few generation scale because it is rate governed by the human brain. In a closed environment, with its peculiar social pressure, the character of the technological potential may have certain operational qualities and limitations. Some discussion of this matter is essential.)

A Note on Social Pressure

The geneticist speaks of a 'selection' pressure placed by the environment on the individual species, which when coupled with a genetic pool which is quite densely packed with mutations, is responsible for genetic diffusion. Most scientists would wonder, not at the aptness of the metaphor, but at the scientific reality of such a pressure. We have demonstrated the physical foundation for such a process for both genetic and epigenetic effects. We have shown that in addition to the two components of hydrostatic pressure in a system (the kinetic component from sustained thermal fluctuations - as short range collisional momentum change; the long range component from intermolecular forces), there is a third component, due to the bulk viscosity, action which 'wells' out of the internal degrees of freedom of a complex atomism (an organism) in response to the externally perceived pressure. The internal self-generated pressure emerges to equilibrate the external pressure (i.e., Man, of all species, reacts to crisis, from his epigenetic heritage). That process is a straightforward physics. It can take place from any internally complex system. If the system internally is stimulus bound (i.e., hard wired, hard geared, hard molded), the response from the interior can only be stereotypic. (Picture a bird beating itself to death against a glass cage wall.) If, as in Man's case, the internal command-control apparatus has a great deal of unstable freedom, then because of the richness of branching paths of comparable energetics - the richness of internal action modes, the internal 'language' of the system - behavior may well out which is not stereotyped, but adapted to the perceived inputs. (A quick note on that theme: Claude Draper, in an Institute for Aeronautical Sciences' Wright Brothers lecture in the mid-1950's, pointed out that what the Wright brothers solved was not the problem of aerodynamic flight, but that of stability. All others, earlier, had tried to create a stable aircraft system. The Wright brothers created a system whose stability, open loop, was very marginal. Stability was furnished by the pilot, the 'steersman' who provided a responsive feedback stability to the ongoing vicissitudes. This was the same notion that inspired Wiener's cybernetics, a product of a number of years of discussion with our colleague, Warren McCulloch.)

The technological rate reaction is one of the major responses of Man, a response in which he differs very considerably from all other species. But these freedoms (abstraction, tool-making, language, branching freedom of action) exact a penalty too. It is not that clear - science fiction to the contrary notwithstanding - that continued isolation of the species is conducive to continuing 'creative' response. Isolated islands and other isolated laboratory experiments suggest degradation of performance at various long term scales (examples: possibly loss of major technological capabilities at a scale of 5000 years and 25,000 sq. mi. territory; loss of breeding survivorship at a scale of 1000 sq. mi. and 10 - 30 generations; in a mouse colony, loss of breeding survivorship is perhaps 10 - 20 generations. These examples do not guarantee any extrapolated results for confined social environments.). The one ingredient which we may assert is apparently necessary for breeding survivorship for long range periods is emigration and immigration. At continent or earth scale, even that doesn't guarantee species and phyla, only a variety of time scales.

Thus in conclusion of this note, social pressure and technological pressure are much trickier thermodynamic variables than generally confront social scientists. Here some guidance from social psychologists, psychiatrists, anthropologists, ethologists, and politicians may be quite desirable. However, one has a sense that these proposed experiments may severely try all such scientific and practical experience, particularly for long term exercises.

Actually we are indebted to our association with the late Paul Siple, who from a geographer's career devoted to Man under extreme stress (starting as Byrd's Boy Scout, in his arctic explorations; as an environmental scientist, during World War II for the Army, and later chief scientist of Army R & D; as an observer of social group interaction during the IGY antarctic expeditions, as Scientific Attache to Australia for the State Department), learned a great deal about the problem, and who gladly swapped knowledge with us. (We consulted for him, as scientific generalists, within the Army Research Office.) Every expedition leader learns to what extent he must improvise from his internal potentials - epigenetic, technological - in order that the group survive. A group effort for a few years may be run as a military organization (SOP's, clear absolute authority, absolute tabus, etc.), but longer terms - at the generation scale beyond - a fuller, freer, kind of social organization has to emerge.

Returning to the equation of state: For Man to survive in a closed environment, it must certainly be open to at least one potential - the radiation-temperature potential which can be viewed as the source of the temperature potential (that is, it is a radiation flux which is the potential as well as the radiation temperature which is a color temperature). There is a limited possibility of useful harvesting of materials in deep space. (This was an area of research we had proposed as a source of high altitude oxygen scavenging near earth. It is perhaps worthy of some exploration as to yield.) All other materials - if transshipping or dependence on other planetary bodies is not envisaged or considered not dependable - has to be carried aboard and recycled. It is an external energy flux which is available for prime design purposes.

The energy cycle for Man under these conditions still has to be essentially the same as on earth. He may be exposed to a neutral temperature environment (e.g., 28 - 32°C), or a colder environment in which there is some discomfort or need for clothing, or some need for moderate activity, or a warmer environment in which evaporative loss begins to increase. In general, one surmises that a near neutral to cool temperature range (e.g., 25 - 30°C) may be optimal, perhaps with some sleep-wake cycling.

Such a prescription already suggests that a considerable degree of design compatibility among the species brought up in the ecological web is necessary, and possibly that the web be somewhat self-regulatory as to temperature. This suggests that a simplest web would be drawn from temperature zone experience. (It is easy to design an elaborate energy costly controlled thermal system. It is much more economical, energetically to design a more nearly self-regulatory system, which is capable of that regulation for a considerable range of ambient space environments, e.g, 'sight' equilibria with a sun, environments shadowed by planetary bodies. Presumably much of that design art, as far as vehicles are concerned, have been mastered with heat pipes. The residue of design we refer to now has to do with interior living web design. Example: Bacteria have a U-shaped division time with temperature. That property could be exploited in a vehicle to help regulate thermal flux.) In any case, in accordance with our growing philosophy, ecological web design has to begin from well tested earth network design.

In such a near constant thermal environment, at moderate activity duty cycle, most of the heat efflux is out from the human body (conduction, convection, radiation, small insensible perspiration). The input energy is also fairly well defined with activity level. Thus the caloric intake is known. We will defer discussion about the materials balance.

The activity cycle has to be perceived culturally as being useful to the participants. One notes that a significant segment-of-life experience is involved in such proposed experiments. (While there is a thermodynamics of brain and behavioral function, in fact one in which we are involved in with neurophysiologist, neoroendocrinologist, neuropharmacologist, psychiatrist and anthropological colleagues, it would be regarded as too speculative to provide that background here. It is one generally left to clinical psychologists. We would recommend that some anthropological consideration be given to the problem. Suffice it to say that both a meaningful long term objective must exist for all personnel involved, <u>and</u> a very well designed flexible short term schedule of life activities has to be designed. The point we have made to deus ex machina rulers - whether farmers, husbandrymen, rulers, drug companies, military commanders, or prison keepers - is that design of action mode schedules has to be loose and flexible at the local level and fit the command-control or nervous system of the species involved. There are very specific constraints on domestication.)

In fact, the selection of an optimal spectrum of action modes does not only extend to Man in the system but to all the species, interacting within the ecological web.

This brings us to what may be regarded, in the narrow, as the major problem in the life systems' design, the regulation of the flux of materials. However, that requires multiple trophic levels of design of an ecological web. In the next section, we thus encompass all four tasks that we were required to address. It pulls together all of the facets of information we have developed.

RUDIMENTARY DESIGN OF AN ECOLOGICAL WEB, A FIRST ROUND OF CLOSURE FROM PHASE I TO PHASE IV

In accordance with the research style that we find useful, we have first established some rudimentary knowledge base of the problem of describing an ecological system in our physical view - how the physics of complex systems (thermodynamics) governs the mechanics and dynamics of interacting living systems; and what are some of the rudimentary facts about the complex ecological system we are attempting to provide integrative design knowledge about. At such a point we always find it necessary to switch directions, e.g., to go on to an experimental phase that will illuminate an integration of knowledge, or go on to a theoretical overview. Since in this phase, we had no charge to begin an experimental program, it was timely to begin a theoretical integration, rather than to continue to fill the information base on ecological components, e.g., on algae, on social insects, etc.

Thus we started a dialogue with our biologist colleagues. The content of this section emerged from such discussion. We are satisfied that it offers a first round of valid answers to the design of a viable ecological web. It is not proposed that our answers will receive complete unqualified support from sophisticated ecologists. Rather it is meant as a study piece to open meaningful dialogue with them, in an effort to define an experimental program that tests both their principles and our principles. We are satisfied that it ties together everything that we know at present. This summary ties very well with our recent study of physical and chemical potentials and how they govern fluxes in fluid systems (8); a new study we have prepared on the physical foundations for all quantized processes (37); a presentation (August 1979), for an international conference on self-organization, such as life forms (38); and recent efforts we have been making to define the physics of living societies, including human, political, and ecumenical (5, 39).

Basic Principles of Design

1. The Basic Biological Law. The object of a biological system is to produce a stable network of self-regulatory biochemical thermodynamic chains that is capable of long term persistence in those forms and functional chains. This we have denoted as 'homeokinesis' (3, 6) in its present application, ecological homeokinesis. As driving forces, basically we are confronted by only four potentials - hydrostatic, including social pressures, chemical potentials, a gravitational potential, and a radiation (e.g., color temperature) potential.

2. The biochemical thermodynamics consists of interlocked chains involving the elemental stable materials, in potential stores and in flux, of C, O, N, H_2O. These are minimal and essential modes.

3. Whereas there likely was a primordeal stable system of organismically chained biochemistry (whose existence is suggested by the possible independence of a third line of living organisms, the methanogens (40), from the other two lines of prokaryotes and eukaryotes), the process relations of that earlier system, older than 3.5 eons, has evolved to the current system. The bottom of the current chain consists of anaerobic methane-producing microorganisms that survive in fairly isolated environments (examples - G.I. tracts, ground and water sediments, sewage treatment plants), where they participate in terminal stages of degradation of organic matter, and live off the CO_2 and hydrogen produced by anaerobic bacteria, which they convert to methane. In other interface environments of atmosphere - hydrosphere - lithosphere more easily exposed to more rapid fluid transports, the other levels exhibiting ecologically mature life forms, the system of interlocking biochemical chains, operate from nine major storage potentials - solar radiation, CO_2, H_2O, O_2, atmospheric nitrogen, earth entrained nitrates, some catalysts (O_3, oxides of nitrogen, oxides of sulphur), gravity, and onboard chemical, 'genetic', codes. (Other small potentials exist which are also essential, i.e., phosphorus, calcium, sodium, potassium, iron, magnesium, and traces of some other elements. These are known to include copper, manganese, molybdenum, chromium, selenium, fluorine.) It is intrinsic to the stability of the ecological system that all nine potentials are available in sufficiently robust reservoirs to withstand the vicissitudes of the environment. Misunderstanding that requirement permits the statistical distribution of fluctuations inherent in the environment to decimate the local biochemical chain to where only very low levels of an ecological chain can survive. This is especially true, the smaller the physical environment and the longer the time of isolation.

4. Current scientific - technological knowledge prohibits any ecological trials that are not based on existing earth experience. The enormous experimental canvas of space and time and environmental pressure on earth, has produced a diversification of interlocking species that is fitting proof that stability of systems living off the potentials has been well tested. On the contrary, wherever the potentials are lost, fragility of the chain has been demonstrated. Fragility, where or when it exists, is in the upper reaches of diversity, particularly those involving Man and his ancestors, and the style of life he has developed. We urge no exotic experimentation. We will be satisfied to try to combine conservatively the best possible results that thermodynamics, biology, ecology, and ten milenia of agricultural and animal culture experience can produce, even if it requires 'reinventing the wheel' in an engineering sense.

5. Autonomy in the ecological web is pyramidal. The lower reaches are autonomous. Subsequent higher reaches depend for their autonomy, in a thermodynamic sense, on the lower reaches. From an experimental point of view, this thesis will have to be tested through all of the nested autonomous pyramidal structures to test out at least the short term suitability of the players and the number of levels proposed.

6. As an extension of some of the current ecological wisdom, the thermodynamic variables in these chains relate to the flux and storage of energy, materials, actions, and population, not solely to any lesser number of variables.

7. While the ecologist will follow cycles of C, N, O, H_2O through the web, and we must follow C through the system but always reentering through CO_2 as a node, the current living chemical chains did not start from O_2 and CO_2 in their current storage forms. These stored potentials had to be in place to permit the life forms of the past 3 eons their interlocked existence.

8. Chlorophyll-like molecules found in blue green algae were an early process by which solar radiation could be tapped, utilized with H_2O and CO_2 stores to fix and build complex sugars. This one step already represents an incredible machinery.

9. For clarity in understanding the life processes, as an intermediary between geochemistry and biochemistry (fitting the Hart model of earth's evolution (41)), the methanogens probably existed earlier in porous rock formation. With no radiation source of energy, they were able to extract atmospheric methane, combine it with atmospheric nitrogen and sulphur extracted from the rock to run an anaerobic chemical cycle. The independence of this cycle and its persistence emphasizes the autonomy and richness of geochemistry on any planet (given some 'solvent' or 'substrate' characteristics) and the dependence and continuing interdependence of organic life forms on primitive geochemical processes. The reason that their sustained current existence requires protected environments is that O_2 is toxic to them, it 'rusts' them out. That doesn't prevent their existence, only their need to withdraw to shielded environments. Life, in other words, does not need O_2 nor does it need the sun for its most primitive existence. It does require a satisfactory thermal environment and chemical potentials to supply the power. Their capability permits them to belong to the same habitat and occupy their own niche as the very bottom of a chain, almost as 'mineral' eaters. They likely are an independent line of evolution, in no way descended from radiation trapping organisms.

However, for the other life forms, trapping of solar radiation represented the breakout in design. But, in order for that process to take place there had to be a rich geochemistry. If nonphotoenergetic complex system forms had to be first, they were. (And in fact, likely can be without necessarily leading to the more complex living forms. This is our basic notion of what may be expected on other planets. The issue of the narrowness of the slot for higher living forms is not thereby resolved. But (41) is an rudimentary example of early physical theory on that question of the the thermodynamic certainty of life forms.) It is then quite conceivable that higher life forms then emerge as a photosynthetic consequence of some byproduct of the geochemical 'mineral' process. This then continues in a line in which oxidative processes (e.g., phosphorylation) emerges as a byproduct of the photosynthetic process. Hierarchical ecological evolution can then open up as a next phase. This line of physical evolutionary thought is worth at least some consideration.

10. However, once radiation trapping emerged, it clearly was highly advantaged, as to diversity, as to mobility, as to fluctuational immunity. Its transport rates were so much greater than the more primitive branch, just as, later, the incorporation of aerobic machinery increased transport competence even another quantum jump, just as thermoregulated species increased transport competence skill another quantum jump (21).

11. However, once radiation trapping appeared, the role of the methanogens dropped to a much slower geological frame of reference (e.g., currently Man appears to be more dependent on their long past history in developing fossil fuel), than in a current interest as an active part of the ecological web.

12. However, it is not only chlorophyll which is a radiation trap. It is not a large number of organic molecules which are found to be useful radiation traps, but there are a few that have been discovered. Rhodopsin, for example, has been 'invented' evolutionarily a number of times independently in the eyes of various living species (such as independently, for use in insect, squid, and vertebrate eyes; their use by bacteria is completely independent) - and where clearly it evolved each time independently as a catalytic molecule capable of performing a biochemical task. These molecules are basically 'dyes' capable of photosynthetic 'fluorescent' transformation of energy, radiation sensitive pigments with a transduction capability to synthesis. The chlorophyll system is quite advanced; the rhodopsin systems are more primitive, the organisms that use the latter operate with much less machinery (e.g., a recent example studied is a halophilic bacterium). Yet within our previous context both radiation traps come early in history.

13. Examining development of transduction systems used in a large number of motor and sensory systems in many species seems to suggest the generalization that once a central thermodynamic engine process can self-evolve, with a certain sensitivity-space-time-frequency domain, in general it can evolve further through the capture of some second principle which results in an extended sensitivity-space-time-frequency domain which 'quickens' or broadens the capability of the more primitive subsystem, without ever losing the primitive subsystem. We suggest that in this sense, the radiation trapping system foreshadows (not 'predicts') a capability for a subsequent system, which happens to light upon onboard oxidative phosphorylation as its extending companion piece. To what extent this second process was obligatory is beyond the scope of this study, but an issue which we prepared to defend at the Dubrovnik conference on self-organization (38). (We intend to present (37) briefly as part of (38).) But at this point we have confined ourselves only to defining the need for a lowest radiation trapping autotrophic level in the ecological web.

14. Our first experimental recommendation is that a number of candidate autotrophs be tested for their thermodynamic capability of being usefully employed in an ecological web. (They make things that the heterotrophs can use.) The alternate to these autotrophs are methanobacteria, but their chemical production rate likely does not match the autotrophs.

15. A stronger recommendation is that one may not start from any 'manmade' synthetic process to substitute for these autotrophs. Thus their optimal selection - later we will discuss the question of increasing 'lateral' (or heterarchical) robustness in these webs - is a matter of basic concern. No science fiction enzyme vats!

16. We move now to heterotrophs. We face two categories - the macroconsumers and the microconsumers. First we deal with the microconsumers, who either decompose or eat the residues of life. They are absolutely essential. (For example, if C goes into trees, that C is never recoverable. That entrainment would fill the entire habitat with tree trunks. Thus a microconsumer - fungi - are needed to return the product to CO_2). At the photochemical level, the materials that have formed, e.g., complex sugars, up through cellulose, have stability. They will not decompose, not even by slow oxidation (they will be burning). Thus a living step of degradative synthesis, occupied with the death phase of organisms, a lower process cycle is needed to return the process through the CO_2 node (or to NH_3). Technologically, the materials can be incinerated. The weakness is that not all atomic materials are recoverable usefully, and what is lost is the 'soil' which higher forms, plants, can use for necessary extractions. It is all of the essential integrative steps that require design. The processes in nature are very carefully matched in their chemical impedance. This is the bottom side of the web, that side which returns material into the biochemical chain.

17. Thus the first real autonomous chain is this pair - radiation capturing autotrophs (e.g., algae) cooperating with microconsuming heterotrophs (e.g., fungi - or single celled bacteria) - which have the capability of running an autonomous chain through the CO_2 node in which sugar fuels are carried completely through the chain. We propose that experimental pairs of candidates be tested for their autonomous competence, say, in the face of various in-the-loop harvesting schemas to determine their autoregulatory dynamic immunity. These must be run in an environment with the nine depot potentials. The pairs are potentially robust in survivorship and regulatory immunity for a wide range of operating conditions. This experiment must be done to test its absolute autonomy. Whether these are to be designed as purely pairs of two, or a range of such species - e.g., lichens, plus algae, plus fungi, plus bacteria - is a matter of getting some interesting experimental design. Generally the energetic cost of fungi may be much higher than for bacteria.

18. But the precursor, to learn the basic rules of thermodynamic stability, is a primary experiment to run bacterial flow systems (discussed in

the body of the report) also. This literally is a test of hydrodynamic stability. Both of these two levels are not really known with the kind of certainty and reliability needed for quantized persistent colonies.

19. This brings us up to the minimum pyramid web - as an introduction to the macroconsumers - what is the minimum higher species as a prototype, who can live in compatibility with the bottom two species symbiot which make up the minimum current autonomous system? This is a forced step in the logic of biology. (This is elementary biology, ecological aspect, reached now from an advanced point of view.) In an absolute sense, neglecting methanogens, we can conclude that the pyramid is botanical. At the bottom level is the autotroph - microconsumer pair, above is a first higher macrobiotic element. A very significant test of such biological elements can be made absolute by seeing what grows when a forest is destroyed by fire. The microorganisms are not destroyed. The first plants that regrow are ferns and grasses. They point up to the fact that the first stable pyramid to test is one with the apex consisting of such plants as ferns, mosses, or grasses (or some combinations such as a mixture of grains). The fact that ferns and mosses grow in shaded regions suggest that their photosynthetic energetics is much less than grasses. As a measure of the strength of stability, it is likely that few animals eat ferns when they are alive. Their age and the degree to which they are preserved in fossil form is an indication of the high degree of stability of ferns in an oxygen dominated atmosphere. They can 'rust' but are not preferred eating. But again the testing of the interesting range of such two level pyramids for stability should be a matter of experimental design.

20. The advantage of having a higher level autotroph is that now it can furnish the amino acid basis of 'nutrition' for species not capable of synthesizing materials from elementary molecules. We note again that ferns almost never serve as the nutritional base for higher species, although mosses do. Thus the basic question that must be addressed among selection of suitable autotrophs (one or more) is the kind of yield of more organized organic materials that might be expected. It is such higher organisms that are going to be macroconsumers. Note that these pyramids require all nine potentials for their operation, and the problem being tested is their competence for autonomous operation, given such a nine compartment storage potential. The system being tested at this stage is a two level system. The use of mixed grains emerges not for any particular symbiotic relation as much as they are to produce a 'rotation' of a growth - death cycle which results in best yields. The design - governed very considerably by plant action modalities - is the kind that results in climax forests or governs plant successions. (See for example (42).) One must note that this minimum pyramid has a relatively short time constant (e.g., a few months to a year).

With regard to stability, which requires test, one might remark that there is a considerable likelihood of stability 'on top,' although at this stage the pyramid may be somewhat brittle with regard to mutation at the bottom.

21. But now the problem is what expansion is required in the pyramid to support Man. Now we are up to a harvesting level (a macroconsumer). In a forced biological sense, this level has to be an animal level, as a third level. The critical issue of synthesis are the amino acids. Animals need all of the 21 amino acids, but Man and most mammals only make 11. Plants on the other hand (not each plant) can make all 21 (in any significant yields. Plant cells likely have 21, but the question is which can make them in useful yields). Thus it is a mixture of 'grains' that has generally served as the annual supply reservoir for 10 needed amino acids (the other 11 being made by the body). This cannot be done by one grain alone (e.g., rice alone, wheat alone). For 'grains' (mixed grasses) the best balance found is a selection or blend of plants plus legumes. Skipping the issue of boredom, we need to answer the question: what is the best selection of second level autotrophs that will best serve a third level grazing animal who harvests amino acids and other trace requirements from the lower two level pyramid.

22. But then that finally brings Man into the picture as a fourth level macroconsumer, who eats off the second level autotrophs and the third level grazer. It is not only the issue of boredom - Man can be a vegetarian, as are the higher apes, but with attention to a very extensive diet selection - Man's specialization has left him with incapability to manufacture a few trace materials that he has additional need for. The advantage of the third level grazer is that these animals concentrate various trace materials which then can most easily serve Man. Thus clearly, we specify stability testing of both a third level and a fourth level system. We shall now specify a little more detail about the second and third levels.

23. One such additional material required by Man is cobalamine (Vitamin B-12). Thus, for example, cows eat grass; they tolerate the extremely large cellulose load, but at the same time they concentrate the cobalamine; we eat the meat and thus get the cobalamine. The principle illustrated here is the basic requirement for matching requirements throughout the chain.

24. So our problem is to select the animal or animals that can provide the match to Man. This can both relieve the monotony, provide a richer temporal spectrum of foodstuffs, and provide the necessary amplifications of some essential missing materials. Thus it is not only meat, but animal products such as milk and eggs that extend the diet.

The alternate of attempting only a three level (phase 4) system, as a pure vegetarian diet, poses very strict rules of nutrition that violate any concept of stability. The four level (phase 5) system, is designed to provide such latitude.

25. Thus we are again forced biologically in our choice of the level three macroconsumer. It is the chicken, not the sheep, goat, or pig.

26. Note there is a problem. The chicken is not a grazer. Food for that species (grain) has to be harvested in a particular way. This stresses,

once again, that the design of the action modal space is critical for the match. Similarly there is the problem of a calorie match, in that only about five percent of the calorie intake of the chicken becomes available to the meat eating Man. So too is the matching of materials, energy, action modes, and population (as its turnover rate), for a satisfactory set of available potentials, which have to include the area substrate available for the system. A number of square miles per hunter-gatherer is fine for a primitive human start up. It is a fantastically small compact space that these long span voyages have to be designed for. And at the present time, we see no first phase study that can deal with any system other than one using solar type energy as a basic source for photosynthesis. Thus we proceed in this first phase with that assumption. It requires highly drastic changes in the requirements for stability to make any other assumption. (But we do not absolutely require external solar energy. Nuclear sources plus conversion to the photosynthetic range of energy is possible as an alternate source.)

In any case tests of their level designs have to be made more to determine their stability.

27. This thesis may be referred to as the "where we are going, there is no MacDonald's; but what do we absolutely need from the supermarket" theme. In such design, we examine, not the up-to-the minute 'tasty' foods that we seek 'now' culturally, but perhaps a little broader, what the choices are in the supermarket. To a very large extent, the supermarkets do indicate the range of choices that people make. Overlooking the broadening of seasonal availabilities, the range of choice is not exceptionally large. The required design, to overcome brittleness, only has to reflect some of this character (and match the time constants for rapid turnover). There are some issues of variety which have to be expanded upon. (The notion of direct harvesting of any algae by humans, with a few artificial flavors, say, is a useless illusion.) Which levels require more variety and storage time constants? These four layers are sufficient, it is only the question of an increase in variety of specified layers.

28. Some of the things required to provide greater stability - illustratively - are the use of tubers for their contribution to higher sugars (i.e., starches). Variety at level two - at the level of plants - is likely the basic need.

29. Very probably a little more variety is needed at the bottom level, because it is likely that a little extra variety at that level (which itself is extremely robust) which can provide support for a great deal of variety and resulting robustness for level two. (For example sulphur fixing bacteria may be required to guarantee keeping this important trace element in the chain.)

30. Ordinarily level two is usually grains, fruits, vegetables, and nuts. The turnover is the issue. Grains are fast. Among fruits, it is

likely berries which have considerable speed. It is not plums, peaches, apricots - requiring long growing trees. A good illustrative prototype is cranberries (as in a cranberry bog). Thus as a modest prototypic mix, we can visualize mixed grains (barley, wheat, beans, tubers) and fruit (e.g., cranberries).

31. The legumes, drawing heavily upon the earth nitrogen potential, destablizes the system. In order to work, whereupon they can fix nitrogen from the air, requires particular bugs. Thus for this component (peas, beans, e.g., soya), it is necessary to add an additional element to the bottom layer, organisms that will continue to fix nitrogen.

32. Some preliminary notion of the self-regulatory process through an ecological pyramid is obtainable from Radmer and Kok (43). The photosynthetic pyramid is fueled by the conversion capture of up to 12 percent of the solar radiation spectrum by plants. A related conclusion is that such a source of autotrophic fixing, say by corn, provided the same yields as are obtained from uncultivated plants. From that point of view, the plant succession of field or forest tells an important story. There is a theoretical foundation of a statistical mechanical nature for the distribution function of interacting, and thereby competing, units in an ensemble. We have argued out a foundation base for Zipfian - Boltzmannian bound ensembles (7). Related is the log normal distribution as is well portrayed in development of abundance and diversity in fields (42), indicating that there is a history and evolution of diversity of species that tend to quickly optimize and equalize the flux of materials and energies through the system. The species establish all their necessary 'symbioses' quite easily after a few growing seasons. (Possibly such 'island' ecologies, if remaining open to immigration, equilibrate their species numbers (44).) With increasing time, there is a lateral growth of robustness that makes for greater regulatory immunity to 'disease'. This stresses again that compatibility testing of the lower levels of a pyramid is quite desirable.

33. The photosynthetic rate inside the plants is not what has limited plant yields. It appears to be the CO_2 concentration in the atmosphere. The design of an ecological web is basically governed by the chemical potential of each of six of the potentials (omitting the radiation, and genetic and gravitational potentials), and each of them could be rate governing, depending on design (and thus these may have to be tested each in turn - for example, earlier, aircraft and mountain experience has probed at the issue with regard to the oxygen potential; environmental physiology at the thermal potentials). On earth, it appears to be the CO_2 concentration (i.e., the current .03 percent concentration). However, it seems quite clear that - in turn - each of the other potentials can be or are rate governing.

34. To illustrate some of the rate governing processes on earth:

(a) Radiation potential or flux. When the radiation flux and resulting temperature potential falls (e.g., arctic climates, or inadequate insolation) the biomass diminishes drastically.

(b) Oxygen potential. At high altitudes (diminished oxygen partial pressure), the biomass diminishes.

(c) Water potential. When annual rainfall diminishes below 20 inches per year (45), the cloud cover is drastically reduced and loss of that potential results in desertification. We have compared our mechanisms for determining the atmospheric potential for water vapor regulation with that of Charney's, who has provided a mechanism for desertification regulation involving the small existing biomass under those conditions, and believe that our two mechanisms (regions of high rainfall, regions of low rainfall) are complementary and account for the differences in their control of low and high biomass.

(d) Earth nitrogen potential. We have inferred from the studies of the International Biological Year, that an ample regulation of the ground nitrogen potential is required to prevent the results seen in overgrazed lands, which then can interact with the meteorological cycle in regions of low rainfall to drive them over to deserts with limited capability for production of biomass, and poor capability for recovery.

(e) Atmospheric nitrogen potential. This potential is seldom rate governing because of its concentration. However, it is the potential for a variety of atmospheric oxides which have - at the present - still subtle catalytic control of the atmosphere. Thus we do not know how to say too much without considerable more exploration.

(f) Atmospheric catalysts. Pursuing the above theme, given the existence of electric charge potentials derived from solar system processes and found in the atmosphere, they tend to help regulate a variety of very complex gas chemistry reactions - e.g., involving O, O_2, O_3; N, N_2, NO,... S, SO, SO_2, SO_3...H, H_2, H_2O, H_2O_2.... Spurred by NASA requirements for comparative studies of planetary atmospheres, there is a youthful science begun by chemical physicists who are attempting to define the complex of atmospheric reactions of these types which are basically driven by solar radiation, and atmospheric and solar system electrical fluxes and potentials. These act as subtle catalysts, that govern greenhouse effect mechanisms in the atmosphere, and act as 'catalysts' for meteorological, hydrological and biochemical processes. The range of their effects in dominating seasonal and longer term biomass is far from clear.

(g) Gravity. We have called attention, a number of times, to the issue of the stability of the genetic code for higher animals such as mammals. (We have no information as to lower animal species, or - say - for wooded plants. We would find it hard to believe that related questions would not exist for these species, in each case where their transport systems are gravity dependent.) In an earlier study (14) we inferred that mammalian design, based largely on perfusion requirements of the cardiovascular system, rather than thermoregulation requirements (a much later development system), is intrinsically tied to gravity, e.g., in the characteristics associated with the head of liquid which all mammalian hearts have to pump against per stroke. If true, then we suggested that the effect of long term exposure to low gravity environments may gradually cause serious drift or shift of the genetic code. At present the limited data we have is persons and species living at 12,000 feet in which oxygen concentration diminution is the more stressing serious pressure. Breeding selection, rather than genetic change, because of the shortness of time (a few thousand years) and the limits in the respiratory system, have already shown significant changes in body stature, but this is not what we are concerned about. It is more the fact that many species already start to show serious cardiopulmonary distress (e.g., edemas) at 5000 - 10,000 feet. Covering the entire range of both breeding selection pressure and genetic drift, by mutation, there is clearly a problem of associating pulmonary - cardiovascular drift on earth with concurrent changes in altitude and oxygen concentration, but an entirely different problem associated with changes just in gravity potential. We have proposed doing 'fast' ten generation experiments with fast breeders such as very small mammals under high and low gravity potential to ascertain whether there is any danger of drift. We realize that drift in a few genertions may not seem serious, but at some point the effects of space colonization or long space voyages with required gravity potentials will have to be faced. (So far, none of the agencies we have approached have been interested.)

35. High power consuming modern agriculture may be fairly efficient in its utilization of physical space but not in energetics (e.g., by extensive fertilization, and running with various of the natural potentials at the marginal edge of their storage capacity). Its outlook and practise, with a highly 'industrialized' (mechanized) use of complex unit processes, is not the direction which would be called for in isolated space ventures - voyages or colonies. Instead what is needed is a highly compact system, e.g., the equivalent of a substrate support system of perhaps 100 x 100 sq. ft. per person, or perhaps even 50 x 50 sq. ft. per person, but using largely self-regulatory 'natural' living systems with a minimum, or at least only a limited number of nearly passive regulating chemical unit process systems. It is with such a design philosophy that we view our five phase experimental program as targeting at for long term survival.

36. Thus a first step to consider is an increase to an optimal photosynthetic yield. (Just as the overall energetic problem - in competition with the biosynthetic yield - is an optimal capture of radiation energy for the other 'mechanistic' processes. Optimization is a design problem that has to be carried out for both processes' compartments. It is not accidental that the problem may be referred to as the generalized optimization of the energetics of food and shelter and other personal needs of the individual. The basic atomic species in total mass and relative concentration are all fixed, i.e., the system is largely closed with regard to materials, except for the possibility of scavenging, or the absolute minimal need for resupply.)

37. Since that starts us off at the specific detailed problem, it is more important that we first complete the conceptual chain. We have now

argued, and it agrees with the findings of others (see for example, May (46), or that entire September 1978 issue of Scientific American) that in general not more than 3 - 4 trophic levels are required (we established the need for four); that about 9 potentials are required; that these potentials are expressed at various levels, basically as chemical and physical potentials, literally as 'pressures'; that these pressures both internally and externally make up the action mode space at every level; that a hierarchical structure is needed that orchestrates the fluxes up and down as well as in and out. With these requirements, a unit 'tree' is possible for some peak macroconsumer (e.g., Man) at the top of that one tree.

With such a specification, we know that there are data sources available by which we can compute the energy, and materials balance at each trophic level (see for example (47)).

38. So the last conceptual question we have to face is what must be done to the 4 level system to broaden its character at one or more trophic levels to increase its stability.

39. As May (46) points out, it has been argued by Pimm that very long food chains may result in population fluctuations so severe that it is hard for top predators to persist (he notes that the assumptions behind the population dynamics are debatable). However, based more on J. Cohen's studies (48) and some other independent sources, we are perfectly willing to believe that food webs have to be compact against fluctuations, and that basically it is optimization in the fourfold space of energy, material fluxes from the potential sources, orchestration of action modes, and population dynamics that govern the issue. Population dynamicists, e.g., May, argue their stability from too narrow a theoretical base. Thus it is absolutely true that stability by population dynamics alone is a very dubious proposition. (It might be right, but it really has inadequate theoretical foundation.)

40. We inferred, from our thermodynamic theory, that a chain involving Man is unstable within 500 years in an isolated territory of the order of a few hundred to a 1000 square miles (by virtue of a fluctuation - dissipation theory) whereby a fluctuation size will wipe the population out (see (5)). The central kernel idea beyond such modeling, of vicissitudinal fluctuations, is shared with ecologists. (See May's article for reports on the work of MacArthur and Wilson (46).) However, our independent reasoning was for chains involving Man, and recent findings for Man on isolated islands confirm these ideas. A most agreeably surprising datum was provided by evidence from a large island of 25,000 mile area, in which it was found that even with many bands present, major food and tools technology regressed in a 5000 year period (49). The point bears out our general thermodynamic hypotheses that there is a characteristic space-time spectrum for human social organization as a biothermodynamic phenomenon.

41. Thus in addition to the apparently more mundane questions of stability related to energy, materials, population (and action) balances (it will require considerable time for readers to understand that movement in

action space and its consequent social pressure is a real physical force. Note the extreme effort we had to devote in (8) to attempt to convince the reader that diffusion is a real physical force), the issues of stability by way of human social interaction have to be faced. A unit pyramid with one human being with his three trophic level subsystems down to a microorganism base is not stable for any long indefinite time. The reasons are manyfold. Nor are two, three or four unit pyramids stable. So we must turn to the issue of the size of a group that has minimum long term stability.

42. Theoretically, the most serious issue is one that we would refer to as the immigration - emigration issue. Before invoking it at the human level - where its seriousness may be the greatest - we can surmise a great number of reasons why, with a given number of unit pyramids, some occasional intermixing from one unit to another may be desirable. That is the unit pyramids are not necessarily run as parallel isolated systems, nor are the trophic levels of each unit pyramid homogeneously mixed. Instead, perhaps, there is a rotation of species, a mongrelization of breeds. We surmise that such 'broadening' practices may be useful with fluctional stability and with regard to the problem of stability for health and disease. This is equivalent to the temporal segregation and intermittent emigration of colonies to produce breeds of maximal stability. They have been exposed to broadening selection pressure.

43. We come to the time scales for Man (neglecting at this point the space scales). We can approach the problem as follows:

Leaders, by holy crusades, or intense personal anger or depression can lead to individuals making a lifetime commitment of their actions in a brief moment (e.g., Kamakazi pilots, suicide, and the like).

Commitment to extremely difficult tasks can be obtained from persons for a few minutes without some basic physiological limitations arising (e.g., oxygen debt).

Commitments up to sustained thermodynamic limits within the body certainly can be obtained for work periods of the order of 3½ hours. (Metabolic activity at the aerobic limit, e.g., 3 ℓpm O_2 consumption for adult males. See for example the devoted effort required to power the Gossamer Albatross across the English Channel, described in the November 1979 National Geographic. Or see the recent report of a conditioned athlete who ran 167¼ miles in 24 hours.)

Commitment to an employer for arduous work patterns, given even a rigid pattern of action mode confinement, can be obtained for a day. With sufficient motivation, many individuals can commit a week of such patterned behavior.

At the month length, only very dedicated individuals will 'freely' permit others to dominate their performance pattern within physiological limits. The enforced imposition of patterns from outside (as in the jailing of prisoners) is commonly associated with deterioration of performance. Great volitional independence of decision making, etc., is not to be expected for outside purposes. Serious psychophysiological behavioral issues (part of the genetic and epigenetic value system and how the action space is dominated) interact here.

Thus the problem of interpersonal bonding (see (3)) begin to be found at this level.

Solitary effort for a year is a very dubious proposition. It is the kind of time scale at which minimally 'friend' pairing, or preferably male-female mate pairing becomes prominent. A committed task at this scale, 1-2 years, is feasible. Thus pyramid pairs at this time scale are possible, and it fits the human action space. What was most characteristic of the human species, right from the start, was a male-female division of labor (5). Of course that process fitted the large roaming range of the hunter-gatherer (40,000 years ago) and even the lesser roaming range of the agriculturist (10,000 years ago). The problem - as modern male-female relations in all advanced technological nations indicates - is that with a confined region, the 'natural' male-female divisions of ancient times is not applicable. Thus pair compatibility is less than an idle problem. It is one that requires careful experimentation.

To jump to isolation for a number of years, e.g., a decade or a 20-25 year generation, this gap cannot be covered by, say, two couples the minimum group who can provide male-male, as well as male-female pairings. At that point we have to turn to our first joint physical - anthropological study (5). We had made a thermodynamic estimate (to fill the action space) that about 25 - 50 people was an 'average' sized band capable of autonomous existence roaming on a land mass (50). See also (51). When we checked our estimate with Murdock's Ethnographic Atlas, a source book on all good studies of known cultures, we found a range of group sizes from 10 to a few hundred for sizes of isolated group cultures, confirming our a priori estimate. (A second population, of 'civilizations' exists for populations above a few thousand people.) However, our anthropology colleague pointed out to us that the groups as small as 10 were already fragmented groups who had no competence for survival. Thus our estimate of a minimum size of the order of 25 stands as a better cut off estimate.

In cultural studies, such groups, bands, have consisted of a number, two or more 'camps', who would at least temporarily band together, held by charismatic hunter leaders. (What made the leaders charismatic was that they displayed altruism in seeing that all camps shared in the food in both good times and bad.) We see little reason for challenging that structure. It is apparently compatible with the action space in the human central nervous system.

A tie-up to all this discussion is that such groups need a sustaining task, a Mosaic-like belief in what they are doing, to stay strongly bonded. Thus about 25 such interacting unit pyramids furnishes us with a first round idea of stability for periods of time from 20 to 500 years (i.e., a group size from about 25 to 200. A level of 500 people is the greatest number of people faces that can be recognized (51), a limitation posed again by the recognition system of the central nervous system. However, spatial stability can easily put social pressure in such a sized group for strong emigration forces). For such a group, a 'life' commitment of 70 years is possible. For sizes much larger than the minimum group, the 'swarming' pressure problem (emigration of portions of groups) becomes quite severe. It is such commonality of problems that could have made it useful to spend time in reviewing the literature on the social insects. We are basing our judgment solely on the human experience (for the more rapid time scales).

44. As a swarming process for social Man, the process is not greatly different than the grow-divide problem of cellular division. The basic encodings (genetic, epigenetic) have to be divided in each group swarming. (A rich illustration of the process was described in the Sciences (52).) This group emigration does not require a 50-50 percent split, but it illustrates the problem of quieting the response of a group to an internalized pressure.

45. A principle for what makes for stability in society is heterogeneous interaction between social atomisms. Thus the individual pyramidal units per person (or their regional segregation in a space ship, with intermittent mixing or exchanging among colonies) makes for stability among the lower levels. It does not make for stability at the highest level of Man, who - without swarming and establishment of additional colonies - can only operate with band stability of different camps. That can be stable with careful intermarriage between camps (a process which has to be considered for time scales greater than one generation time). With severely limited resources there is considerable merit to traditional societies.

46. The serious problem that may have to be faced is the spatial one. For stability, the roaming range of a hunter-gatherer group would generally have to be in the 100's of square mile range. Can one do this in a small minimal substrate habitat (2000 - 10,000 sq. ft. per person) in space (i.e., space ship) for a generation or two? There is hardly any known answer. It may be possible, with occasional touchdowns and a round trip goal (i.e., Ulysses' 'Argosy'), that the explorer band type effort could be supported for a longer round trip voyage. Or it may be that settlements on foreign planets (Mars, moon) with a swarming or tour of duty interchange capability, resembling hunter-gatherer band experience, might have some success. At least there is a past experience that says it is possible.

47. If the experience of a number of millenia are respected, with regard to groups and swarming, extremely serious problems in a community, such as plague or other diseases, have the effect - at most - of producing decimation (reduction of size to 1/10th). Thus one must expect there to be some biological losses and some chance involved in establishing minimum colony sizes. Accepting such conditions, settlements in foreign planets might even be feasible for periods of the order of 500 years, without renewals.

48. Clearly, as an enhancement of robust stability - as is found in social insects - if and when a particular genetic (or epigenetic) strain falls out (e.g., a hereditary group of leaders dies out) it is quite likely that the 'encoding' derepresses, as it were, and the action space is filled by new leadership. (See for example recent work reported by Meerkov (53). A fraction of bees, whose behavior had never performed a particular type of behavior, if certain types of bees were eliminated who had heretofore been considered to be performing stereotypic behavior of their class of bees in the hive, would now begin to perform that behavior. Experimenters are beginning to learn about a great deal more plastic behavior even in social insects than they had heretofore inferred. Their societies are not as brittle as has been considered.) This process must be recognized and allowed sufficient free rein in the charge mission of such groups.

49. In reviewing our findings, our biological colleague - consultant stated in conclusion: "If this design job is (at least in the preliminary scientific research, or R & D phase) given to industrial society oriented specialists, e.g., engineers with specialized interests, such as food manufacturing, chemical engineering unit processes, transfer operations, assembly lines, control engineering, without consideration for action space and the rules for filling out that space and stabilizing it (i.e., using Procrustean bed fitting), their systems will be designed brittle, and the systems will likely fall apart, regardless of the size they built it. This design requires a God-like deus ex machina. So look to the designs that nature has used."

We solicited and obtained a first round of review of our tentative conclusions from other biological and ecological colleagues. They were satisfied that we had made out a general case of considerable persuasion, sufficient to start a second round of detailed criticism and modification of emphasis. Within the scope of the contract, this seemed as far as we could go for a first round.

Thus, instead of embroidering further detail, we turn for a last topic to what we believe to be the most serious problem for closed system ecological design, that of stability.

ECOLOGICAL STABILITY

The problem of ecological stability is likely the foremost theoretical problem in that field, whether it has surfaced to the attention of all people working in the field or not.

1. <u>The thermodynamic question</u> - Consider the scope of problem being asked: If life is so commonly described as an 'open' thermodynamic system (open both to material and energy fluxes), what is one to make of the question: Can one close such a system, [illegible] in particular to material flux, and expect it to survive? Obviously, if the system is closed with regard to mass and energy, it cannot survive. (We might qualify that problem with the question: Could we close the environment of a spore indefinitely and have it survive? We think we know the answer. We can conceive of active machinery being turned off so that all engine processes are halted, phases stilled, so that only internal uniform thermal fluctuations are going on. Nothing else is going on. Then the only process of degradation, in the inside, would be mass diffusion between phases. In solid state phases that can be very slow so that stasis for perhaps approaching 10^8 - 10^9 years might be conceived of. Reopening the system back to energy and mass flows might then be used to retrigger start up. At least, we believe we could build such a system. But that state of stasis is different from having 'normal' active processes going on in the system. That is what we will to mean by a system surviving.)

So we ask the lesser question of closure in which input flow of energy is permitted but not matter. We may start to address that question with the following problem: Somehow it begins to provoke the question of stability.

2. <u>Stability in the large</u> - The earth, 'spaceship' earth, as it is referred to, is basically closed with respect to materials (for 5 billion years - we overlook the eacape of earth constituents which is not essential to our argument about the maintenance of life, although it may have been of concern to start up) but not to energy (solar radiation, absorption, and reradiation, via the greenhouse effect, at lower effective temperature). Life has persisted on that planet for just about 4 billion of those years. Has the issue of closure been tested in that experience? That question at least offers one experimental point (or lower boundary) for a theory of some aspect of stability, if it can be developed.

As we approach smaller sized 'closed' fields, we begin to find a little more data, some from ecological studies, some from anthropological studies. We may ask, first, if the entire earth has been open to biological species, how can one find isolation?

Basically that arises from the equation of state characteristics of living systems. As we have shown, using a bacterial field as an example, living systems cluster in a niche, a region in which they can satisfy their conservations. Living systems condense, cluster; they do not spread out in uniform density. Their clustered ensemble movements away from such a niche are diffusive; very little of individuals moving out, but more often of swarming or emigration. Within the niche, the movements are propagative and rapidly diffusive. In toto, we have characterized the physics of such movements as a hopping Brownian motion (38). Physically the process resembles an evaporation-condensation in a liquid-plastic state. These are all issues concerned with a theory of matter condensation.

Within such a broad field, the earth as a general habitat, there can be no absolute isolation. There are just lesser and greater impedances to directed diffusion. However, as the directed diffusion rate is modified, e.g., slowed down, there can be sufficient time for historical, developmental, or evolutionary processes to take place. Hunter-gatherers attached to and diffusing rhrough a poor land do not develop a great deal of historical presence. Death by deprivation of fundamental conservations may take place nearly 'instantaneously'. Death of a breeding group can take place in one or a few generations if conservations in the local field are not supported by renewal (e.g., by crop rotation). The human epigenetic heritage begins to deteriorate within a few tens of generations. Species changes take place at scales above 50,000 years. Thus the kinds of change that may be found depend on the nature of the isolations.

For ecological chains involving Man, a particular 'ecumene' of interacting groups has been found to deteriorate seriously in its technological potential over a period of the order of 5,000 years on an isolated island ((49) - the society regressed and forgot how to fish) of the order of 25,000 square miles (1 observation). There is also evidence that a more minimal group of up to a few hundred people are not assured of persistent life in 1,000 square mile isolated regions (islands) for more than a few generations.

Such data are nearly anecdotal, but they are representative of the little that is known about human isolation. A log-log plot, covering a range 1 year to 5 billion years, suggests stability of life form that varies with isolation area to a power (i.e., the 5/3 power). This representation has at this point no theoretical foundation other than a surmise that biochemical evolution is both a thermodynamic process, and one that takes place by discrete quantized jumps within the substrate or support field to which the life process is attached. This may be regarded as a hypothesis or surmise.

Note that this surmise was made for niches that included Man, that is, these were fully 4 trophic level systems. There are more data available in the ecological literature on more limited level systems.

While this notion is only a surmise, which is quite speculative and highly global, nevertheless it provides some kind of limitation to the scope of the problem, one that is compatible with thermodynamic reasoning and the crude data from a variety of sources. It says that all systems have a birth, life, death process scale tied to the physical environment that nurtures them. It says that such a notion is in fact true for the living system itself. It says that if individuals are born and die (a scientific thesis that has been known for millenia), and species and even phyla (that knowledge is only derived much more recently; see for example, the body of literature which Gaylord Simpson has pioneered in), life itself has to be confined by a physical scale. The three points 'assumed' to provide a linear scale (in the log-log variables of area and time) already provide a 'prediction' for the scale of phyla which is reasonable (it also does not falter, as a vague conceptual relationship, down to quite small social space-time).

But what is most interesting, from a stability point of view, is that any conception of what might lie underneath such a relation is dynamic, thermodynamic. The field cannot be occupied during the lifespan of its 'life' as a static process. Instead it is a basic fluctuation - dissipation process. We would recommend Part I of Darlington's monumental book (54) as the profound view of this process as a geneticist-historian captures the theme.

The speculative relation we have offered is a diffusion relation. It is a relation between the velocity of diffusion and the life of the system. To illustrate the spirit of the relation, even if the precise numbers are suspect:

Life Years	Diffusive Velocity mi/year
1	3
10^3	0.3
10^6	0.03
10^9	0.003

To question what sort of kinetic physics lies behind such a result suggests not so much a hard unity of process, but a unity of dynamic principles by which a uniform scaling of diversity and complexity of internal function is found in the space-time domain in which the process unfolds. If a system consisted only of one ensemble level, extending indefinitely, we might expect a constant diffusion velocity independent of life. But if each level of organization is followed, more or less uniformly, by succeeding levels, then in each case, new spectral processes are involved in life, and the diffusive process expands increasingly slowly. Loosely speaking we will surmise that fluctuation - dissipation takes place uniformly at level to level of organization, from the single cell, to the organ, to the organism, to the social band, to stratified societies, to the widely broadcast civilization, to the interacting species in niche and habitats, to the entire ecology. The expression of that relation is not a physical law, but a physical strategy. It is a strategy like evolution is a strategy for biochemical processes; like otogeny recapitulates phylogeny is a strategy for developmental processes. The thermodynamic law, for complex systems, is that no atomistic level of organization can equilibrate to rest. Instead a cyclic near-equilibrium of fluctuation and dissipation will exist which, combined with propagation and convection, will create a diversity of form and function. That diversity will be expressed as change in the formal character of flow fields, or as change in the state of the form of matter systems. For living systems, at the genetic level, this will consist of speciation and extinction. At the generation level this will consist of emigration and niche settlement.

The spirit of that thermodynamic 'law' was captured perfectly by Newton, long before an atomic theory of matter was satisfactorily founded physically, and long before a theory of thermodynamics existed. "Now the smallest of particles of matter may cohere by the strongest attractions, and compose bigger particles of weaker virtue; and many of these may cohere and compose bigger particles whose virtue is still weaker and so on for diverse successions."

If some such relationships lie behind the life characteristics of a living system, then they impose very severe limitations on attempting to create a long lived thermodynamic system in a small space. We would surmise that various changes that have taken place in, say, the human species (we select that one because it is the one of interest to us) in the history of biological - technological adoption is related to these questions. As technological changes were made from hunter-gatherer with tools, to incipient agriculturist, to slash and burn agriculterist, to three field agriculturist, to agriculturist making use of synthetic fertilizer, the space-time scales for isolated groups have changed. The only problem is that the experience with the last phase is much too limited, and it is far from clear at what space-time dimensions an isolated life can scale. This argument leads us once again to the conclusion that life stability in small scale has to be governed by the best long term know-how of 'dirt' farming within such a system. Those technological adjuncts which contribute regulatory competence by means of slow reliable processes are to be preferred to high speed control processes which are costly in the total energy budget. In any case, one senses that the system's components and levels require regular turnover (e.g., random or periodic rotations) rather than a dependence only on static positioning.

An underlying implication in this description is that in a long space isolation or voyage, the problem of survival itself has to be a major task of the system, with any other scientific goals secondary to that of determining conditions of survival. Thus the composition of the living participants in such experiments have to be assembled with regard to their competence to contribute to that main goal. One can raise serious doubts whether the current political climate is ripe for such adventures. (There were various times in past history when the political-cultural climate was ripe, so that such experiments are not precluded forever.) Nevertheless, as a scientific-technical exercise, it is possible to name minimal requirements for some feasible experiments.

However, for the sake of the exercise, we can adopt some conceptual scenarios: colonization on the Moon or Mars, or a long space traverse of the solar system. The problem, in each case, is that there is no quest of that nature which has sufficient purpose, at this time, associated with its achievement. The various unmanned satellites and the orbital lab - space shuttle program seems to satisfy immediate needs. Thus at best 'short term' colonization by people (e.g., tours of duty for a number of years) would seem to fulfill any other extended purposes. The one exception to this conclusion is perhaps the single question of whether complex life forms could themselves be so isolated. Thus it might seem that a closed system isolated on earth and on the Moon or Mars, without Man, except as an intermittent observer, might be a useful experiment. The purpose of a non-earth colony would be to test out the problem of life in a low gravity field. As we have indicated a number of times, there is a question as to the stability of the genetic code under low gravity. While our specific question was raised at the level of mammals, there is little doubt that some similar process (viscous flow resistance versus the requirements of developing a pressure level for gravity) would be involved in other living species.

But under these conditions, one is then left with a very interesting experiment which does have considerable significance to Man. Is there stability in a closed ecological system of a specific size (given only known energy input)? The answer to that question, more realistically than the highly speculative data points that have been provided, would provide some measure of how living species can and do survive. One notes that the one 'paradisiacal' mouse experiment of John Calhoun's failed. Experiments of this sort, including their design, are likely more serious - for the future - than anyone has yet given attention to.

The merit of conducting such an experiment on a low gravity environment is that it intrudes one of two major environmental variables that ought to be tested.

3. Testing living system potentials - The living system operates from a limited number of potentials - the radiation temperature potential, a variety of chemical potentials (for materials and energy), gravitational potential, and a hydrostatic pressure potential. At present we would view the temperature potential and the chemical potentials as being essential. There are only two potentials which perhaps may be unessential, or perhaps not, and therefore worth testing, are the gravitational potential and the hydrostatic pressure potential.

On earth, there is evidence that the hydrostatic pressure potential may be of some significance (although it is entangled with the temperature potential). At hydrostatic pressures below 100 mmHg (e.g., an atmosphere totally made up of 100% oxygen), one suspects inadequate pressure for higher life forms.

Low pressure environments could be tested out on earth. (By low pressure, we mean an environment with little or no 'inert' gases, only a variety of small vapor pressures, and minimal pressures of essential gas components such as O_2, CO_2, and oxides of sulphur and nitrogen.) Relevant levels would be such magnitudes as 400, 200, 100, 50, 25 mmHg.

However, the test of a low gravity environment is obviously best achieved in space, in which the Moon or Mars are suited environments. Some possible economic or other national benefit for maintaining such colonies other than the principal one of testing out living system stability is not factored in at this time.

4. Mathematical stability - How may the issue of dynamic stability be addressed? We are well aware of the questions in a mathematical - topological - sense. Linear stability is the dynamic stability of a system at rest, singular points of motion of which all time derivatives vanish, and which - under any small perturbing disturbance - the system will return to. That is not our concern. Linear stability is the problem associated with one or more particles, e.g., sand particles, which come to rest on a solid plane and can resist moderate disturbances.

There is limit cycle or orbital stability in which a particle locks into a closed orbit such that - after disturbances to that orbit, slowing down, or speeding up - the particle will return to that closed orbit. This requires both nonlinear and dissipative processes.

The only other stability known in the stability associated with the so-called attractor basin of 'noise'.

The problem we have to face is what sort of stability would suit a closed ecological system? First, since we insist that it be thermodynamic, we cannot deal with any stability that does not require dissipation and persistence of motion. That would seem to leave only limit cycle stability as our choice. However, in order to involve such stability, the orbital motions of limit cycle stability appropriate to a system with one degree of freedom has to be extended. Limit cycles must exist for each degree of freedom independent of the other degrees of freedom. We have developed such notions in (38). Loosely speaking the relaxation time processes of interacting atomistic-like entities comprise limit cycles. Thus a complex atomism running through a cycle of its internal modes defines such a limit cycle.

However, if our concern is with species survival, then the limit cycle has to relate to the generation time, and if our concern is with a group of interacting species, then we have to define a longer time process for which we have no assurance that a limit cycle exists.

It is that latter type of system's problem whose stability is of concern.

We can use a recent article in Nature (55) as a foil for our argument. Their lead theme is "It is still not well understood how large complex systems (such as ecosystems) come into being or how they persist over long periods of time." They point out that the existence of such systems presents no problem if the teleological assumption is made that variables are compelled to adjust their mutual interactions in advance. Otherwise there is. So they move to the alternate question of how a randomly interacting system arrives at an equilibrium.

To test their questions, they address the mathematical set

$$\frac{dN_i}{dt} = N_i \left(r_i + \sum_j A_{ij} N_j \right) \quad i = 1 \text{ to } M$$

with equilibrium values N_j^o given by the matrix equation

$$[A][N^o] = -[r]$$

M species

N_i = population density or biomass

r_i = increase rate

A_{ij} = interaction constants.

This represents first order reaction rate equations with predator-prey coupling from other species and with a logistic or quadratic term saturation (e.g., $A_{ii} = -1$). They view it as a generalized Lotka-Volterra model. Stability, in their analysis, is dependent on all the N_i^o being positive, A_{ij} having no positive real parts; if such criteria are satisfied, a stable 'homeostatic' equilibrium will exist.

By study of a 'random ensemble' of A_{ij} and r_i values (according to particular rules for creating the random ensemble of values), they find a subset of homeostatic systems. But there is a necessity for all species to be self-regulated, $A_{ii} < 0$ (i.e., that there be a definite logistic saturation). However, the chance of obtaining homeostatic systems from such a random collection of species was too small. Thus they tested a second 'selection' mechanism.

They eliminated species with the most negative values of N_i^o and tested the residual collection of species to find if it was homeostatic. By that procedure they found that systems would become homeostatic at about half the number of original species. Thus, in their view, they had arrived at a 'natural selection' process intrinsic to the model. As compared to testing assemblies of M species until a homeostatic one appears 'naturally', they estimate their process of 'natural selection' to be nearly a millionfold faster.

This is an interesting paper. It makes use of many of the key ideas that demographers, mathematical thermodynamicists such as the Brussels group, and many others have used as a reaction kinetic model of ensemble interaction. Yet, in our opinion, the model is of dubious value. As we indicated first in a 1975 invited AAAS session (see (50)), omitting the predator-prey regulation, the only population law thermodynamically feasible for a homogeneous population (i.e., a population of cells that multiply by division, or of families that multiply by sexual reproduction) is

$$\frac{dP}{dt} = kP$$

where

$$k = b - d$$

in which k is severely bounded after a characteristic time scale near zero (that is birth rate and death rate are nearly equal, and basically fluctuate by entwining around each other).

Some further support for this reversal of Malthus' view, in which population is not viewed as an independent variable whereas its regulation is (via k), may be found in a population colloquium (56).

The thermodynamic problem is that as a result of coupling via other thermodynamic compartments, a choice function emerges for the species - the current birth rate, as compared to the effective birth rate a number of generations prior - to determine the single reaction rate constant k. That 'constant' is not the 'cause' of population change, but the effect.

It is not the case that no systems exist which have a functional limitation

$$\frac{dP}{dt} = kP\left(1 - \frac{P}{P_o}\right)$$

where k and P_o are constants, but these are very specialized. It is a logical confusion to impose this mathematical formalism on the living demographic problem and expect stability to be decided by these issues. The topology is wrong.

This challenge is of such a fundamental nature that it will not be broached again until taken up by suitable topologists who are so much more competent than the authors to pursue the subtle mathematical arguments. However, by making that assertion, it becomes useless to pursue arguments that one finds in the literature discussed by such people as May (60). Also see (61), (62), (63), and (64).

5. Efficiency limitations - If one turns instead to the feasible near steady states possible in a system, ecological literature has provided useful data, which we will touch on lightly. By uncovering this kind of data, we can return to the question of the governing stability in multilevel trophic systems.

References (43) and (47) are useful introductions to the problem of an ecological system. They suggest that such systems are strongly rate governed. In some basic way, each level moves up toward an equilibrium Malthusian law

$$\frac{dP_i}{dt} = k_i P_i - \sum_{j \neq i} \ell_{ij} P_j$$

in which the population moves toward equilibrium, exhibiting at most random or periodic fluctuations. The bottom levels are limited by the capability for photosynthesis. The theoretical maximum attainable conversion efficiency from sunlight is about 10%. Measured in units of the solar constant at earth's position ($h_{\odot} = 1$ cal/cm^2 min), with 40% sunlight averaged for the day, a m^2 of ground area would receive about 6000 kcal, and photosynthetic plants should be able to fix about 600 kcal per day. This should be able to reduce about 600 gm CO_2 per day, or produce about 150 gm carbohydrate per day. However, the best yields observed are perhaps 30 gm carbohydrate per day, and commonly more like 3 - 10 gm per day. Thus, for example (47) shows that in a hardwood forest, a solar radiation of 6000 kcal would fix about 130 kcal per day.

In reference (43), alluding to Pimental et al. (1973 Science article), of about 6000 kcal insolation, about 80 kcal in useful food (e.g., corn kernels) is produced (i.e., 20 gm carbohydrate per day).

With these bare numbers, and the notion that what makes ecological systems stable is their high degree of overdamped dynamic performance (there is little feedback from level to level, and each succeeding level is only a moderate load on lower levels), we can make a very crude first estimate for closure (on an earth environment). We assume that 3 gm per-day of useful food can be assured per m^2. A daily requirement of 600 gm would require 200 m^2. Because of the highly damped nature of the web, we assume that double the area is required to supply both the plant producer and the microconsumer of detritus. Thus 400 m^2 could supply a high level animal grazer, e.g., a human. However, if an additional level grazer were introduced to satisfy the meat needs of a human, we assume that this would receive an additional doubling of area, i.e., 800 m^2. Are these numbers feasible?

Fortunately there is experimental garden work reported on in (57), in which a horticultural researcher, Jeavons, reports that with a low technology strictly organic method of intensive gardening "it should be possible to grow an entire balanced vegetarian diet for one person on only 2800 square feet [300 m^2] in regions with only a four-month growing season." This, he points out, should be contrasted with 32,000 ft^2 required in India, or 10,000 ft^2 commercially in the United States for a vegetarian diet, or 22,000 ft^2 for an American meat diet. Doubling the vegetarian estimate, leads to an approximation of 600 - 800 m^2 for an American diet per person.

We realize quite well that our mode of making an estimate is quite crude, but in essence it does not really differ from highly sophisticated estimates, and it is based on the highly overdamped nature of ecological webs. We are especially sympathetic to the Chadwick-Jeavons kind of results, not from any organic food mysticism but because - in tune with such efforts - we have been advocating low materials, low cost, highly sophisticated technological concepts as the required American solution to ecological - economic - technological problems. These demonstrations (57) have not been 'high technology' solutions, but intensive state-of-the-art horticulture. We believe that there are ideas even more sophisticated available for solutions, but at least they demonstrate minimum levels that can be achieved. In any case these numbers agree with estimates we have made, in which we have proposed to undertake research to explore and demonstrate modes of producing food sufficient for a community of 25 - 50 people on a research plot of 6 acres in a long term near equilibrium mode.

Without commenting on the technical merit or means of achieving even higher yields than are currently state-of-the-art, we would note, for example, that (43) points out a possible doubling in the rate of photosynthesis by CO_2 enrichment. A much more speculative proposal may be found in (58) for possible biomass yields beyond the current theoretical photosynthesis limit. The scheme uses an iron oxidizing (ferrous to ferric) bacteria in which the ferrous form of iron would be produced by solar (thermal) energy conversion.

In reviewing all of the extremes by which stability and efficiency in an ecological web might be sought, one point is clear. Each solution domain has to be tested as to its stability, around its own singular point of equilibrium. Thus these require independent experiments.

Our own tentative conclusion is that for consideration as a closed system (whether conducted on earth or elsewhere) for indefinitely long periods of time, it is the sophisticated low technology, intensive horticulture design which has the greatest merit. However, other more complex technological solutions can also be designed for. But in all cases, it would seem that the most desirable experiments would be to test out all competitive experiments as fixed installations, e.g., on earth, on the Moon, on Mars. A fair enough sequence of experiments are closed installations that lead up to Man; e.g., a two trophic level, three trophic level experiment in which Man is only an intermittent observer, or replaceable by tours of duty, and then finally four trophic level experiments in which Man is locked into the experiment for a long period, involving more than one generation.

We can think of scenarios, involving say replacement of generation time scale (e.g., 20 - 25 year tours of duty) in which dedicated groups of people could be usefully employed, and be convinced of such useful employment, on a remote Moon or Mars station. Any steps beyond such first steps strike us as being more fiction than real at the present time.

With regard to the crowding in the camp, we can offer one scenario with a piece of supporting data. That is if we questioned whether life associated with a camp space of 3,000 - 10,000 ft^2 per person was feasible for a generation time scale, we can turn to an article in Science on the ! Kung Bushmen from the Kalahari Desert (59). As hunter-gatherers, they live in camp areas, with an average space of 200 ft^2 per person (camps with about 20 - 40 people). During the day, about two-thirds of the residents are at home in the camp. However different from crowded urban populations, parents can control the movements, associations, and activities of their children, who are closely associated with the adults. The children have no place to go; beyond the camp space, there is only a vast undifferentiated bush. (As a measure of high urban density, the current population of Hong Kong is crowded into a density of about 12,000 people per mi^2, or about 2000 ft^2 per person. One notes that the design problem is associated with high urban densities, and thus requires a great deal of cooperativity.)

6. Turnover considerations - In any case what emerges from the considerations of this section is that a major problem in the design of a multitrophic level ecological web, for stability, is that the turnover fluxes at each level have to be well regulated, preferably autoregulated, and that a major function of any higher level user - more important than the utilization of the lower level for food - is to maintain the turnover flux at a suitable rate. This may strike some as a peculiar role for the shepherd of a flock, but one must believe it to be the major role that the harvesting user must grasp and play.

Of course, one physical domain in which this issue of turnover is quite serious is among the trace elements that are essential for life. Precautions must be taken to insure that elements that may be concentrated at some living system's level are returned into the cycle. It is of interest to note that beyond current dietary allowances for various elements, the National Academy of Sciences will now also recommend dietary allowances for trace elements Cu, Mn, Mo, Cr, Se, F.

7. Coupling and diversity in ecosystems - The dilemma faced in this study is that the literature on ecology has not succeeded in developing models that are dynamorphic (agreement in both form - morphology, and function - via dynamic laws) with the real physical system. Such a theoretical model could not be developed here in a one year exploratory effort. What we have done is to pin down the physical - thermodynamic - basis for such a model. As we have indicated, it has to involve dealing with four classes of conservations. These are materials fluxes, energy fluxes, action fluxes, and population fluxes. State and rate balances have to be developed for each compartment. These balances do not exist in detail. Thus any effort to really consider stability has to be based on cautious and tentative proposals and experimental verification.

For some sense of the issue of stability and diversity, one still has to turn to experimental studies. Gosz et al. (47) and Cohen (48) illustrate some true character of such diversity. An introduction source of some system's analysis is three volumes edited by Patten (65).

For a review on agriculture ecosystems, see Loucks (66). Other data sources are the National Academy of Science reports of the U.S. National Committee for the IBY.

A source for what exists today as a theoretical system's ecology is a book edited by Halfon (67).

CONCLUSIONS AND RECOMMENDATIONS

1. Experiments should be conducted at unit sizes of the order of 2000 ft^2 (e.g., 20,000 ft^3) on very selective 'dirt' farming 'greenhouse' enclosures on earth to attempt to develop a four trophic level stable closed system capable of support a human adult for a number of test seasons.

This recommendation encompasses an entire set of conclusions drawn within this study. It assumes that, if a number of such test sites were designed - basically independently - by a number of investigators in a variety of temperature zone locations, a useful number of successful operational units would be demonstrable.

The purpose of a number of such successful units, besides the competition to produce an optimal success rate of good practise, is to produce units that can be combined in some optimal cluster for a real coordinated experiment.

2. By current design criteria offered in this study, a basic module for long term (e.g., generations) occupancy by human beings would involve perhaps 50 such modules (i.e., covering an area of perhaps 2½ to 5 acres).

This estimate was arrived at as the nominal size of the minimal social group for which long term (generations) survival might seem assured.

3. Design of four level pyramids should be tested in experimental plats (100 to 1000 ft^2), loosely according to the following sequence:

(a) Bottom symbiotic levels of one or more autotrophs linked with microconsuming heterotrophs (e.g., algae and lichens, plus fungi and bacteria) in which a variety of harvesting schemes and schedules are tested to determine the autoregulatory immunity of this level.

(b) A first pyramid consisting of the bottom symbiotic level plus a higher macroconsumer plant level to determine the regulatory immunity of the pyramid to a variety of disturbances. The plant level should be a mixture whose harvesting suits human beings and a third level animal harvester. The plant mixture might consist of a selection of mixed grains, legumes (barley, wheat, beans, tubers), and quick growing fruit (berries).

(c) A second pyramid consisting of the previous pyramid with a third level macroconsumer. The best selection of that level appears to be the chicken.

(d) A pyramid involving the fourth level human being tested at full scale size of 2000 ft^2.

The expectation, from such experiments, is to determine the impedance matching in flux and turnover at all of the essential material, energy, population number, and action modes among the various levels, and the immunity in storage capacity against fluctuations.

4. For such systems to operate, it is necessary to recognize that they are supported from a number of major potential sources and various minor potentials. The major potentials are: the input radiation flux (the system is basically powered by an energetic flux); the radiation temperature potential (e.g., a black body radiation temperature); major biochemical chains existing as storage chemical potentials - CO_2, H_2O, O_2, atmospheric nitrogen, ground stored nitrogen, sulphur compounds, phosphorus compounds; many minor stored chemical potentials - sodium, potassium, calcium, iron, magnesium, copper, manganese, molybdenum, chromium, selenium, fluorine, others; gravity; onboard genetic code; and, in the case of Man, the epigenetic value potential (memory of a cultural and ethical heritage) and the technological rate potential (not only the memorized knowledge of existing tools, but the capability of creating new tools).

The basic assumption, for stability, is that each of the lower pyramids has to be stable in their own right and not dependent on the higher levels for their success. Thus the lowest level has to be self-regulatory with or without extensive harvesting from the level of macroconsuming plants. The pyramid including plants has to be self-regulatory with or without harvesting from the third and fourth animal levels. The pyramid including a third level animal harvester (or harvesters) cannot depend on Man's harvesting for its operation. Thus the fourth level pyramid, including Man, can only change the nature of the operating point, but not the self-regulatory character of the system.

5. The systems being proposed for test are viewed as an overdamped chain, that is each level is self-regulatory with or without the limited harvesting of a higher level. This scheme makes use of very little feedback control. Instead it depends largely on self-regulatory processes inherent in the action mode spectrum of each user level. It is proposed that this is the key system whose stability must be tested for long term survival, as compared to any other 'higher' performance system based on extensive but energy costly feedback control schemes.

We would regard the major application of technological augmentation to the system (other than the basic schemes for energy trapping) to lie in 'facilitated diffusion', that is schemes for modifying the conductances or turnover times. This would mean, for example, that historically evolving tools are expected with materials at hand that fit Man's manual capability; simple regulatory mechanism schemes that are assured of long life, renewability, and available repairability can be included.

6. Subsequent to or concurrent with the development of modules on earth, similar life components can be tested out in space (e.g., space lab experiments) to qualify such components for a full scale unit (e.g., one or more 2000 ft^2 units) assembled on the Moon or Mars.

The purpose of such tests is to determine whether self-regulatory 'pods' are in fact capable of supporting Man in the low gravity of space, and in fact are capable of self-regulatory performance with or without Man present. Such experiments can be conducted with Man observers for tours of duty for a few years. Such experiments literally would succeed in putting Man in space.

7. Success with a few pods over a number of seasons might then be followed by the experiment of a longer life colony of perhaps 50 pods. Such a colony ought to be capable of survival for generations. However, decision to undertake such experiments will depend on political factors, not scientific factors.

8. The alternate experiments of developing and assembling pods in space, e.g., in stationary orbits near earth, as preliminaries to orbital traverses through the solar system, should depend more on the engineering costs to deliver such pods and occasionally service them either on a regular basis or on an emergency basis. These costs will change in time.

The purpose of this investigation was not to conduct such engineering study. Thus little more can be said about the selection of options.

9. In any case, it would seem clear that the issue being proposed for test is the feasibility of assembly and the stability of minimum pods capable of autonomous support of closed life systems including Man, in the face of disturbances.

It is an amazing thing, but the answer to such questions are still not known to Man on Earth. Just as a deepening of Man's understanding of his own total environment - atmosphere, hydrosphere, ecology - has been deepened by the NASA comparative planetary missions, it is now interesting that an understanding of Man's survival on Earth is being deepened by this proposed comparative ecology mission.

10. An obvious recommendation is that a base study of Earth ecology be undertaken, in which the systems that are essential for Man's survival be examined from a thermodynamic point of view. These interacting systems are six: the lithospheric earth, the hydrosphere, the atmosphere, the geochemical sphere of earth, the biochemical sphere, and modern societal Man. We would recommend such study for a possible future phase of work beyond this.

11. As a final recommendation, we recommend that intensive study of some primitive flow systems - e.g., bacteria, algae - be undertaken to establish some base information about thermodynamic equilibrium and stability in many generation long life living systems. Such experiments are described in the text.

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