Energy Vol. 4, pp. 1107–1117
© Pergamon Press Ltd., 1979. Printed in Great Britain

MARCHETTI-076

0360-5442/79/1201-1107/$02.00/0

10^{12}: A CHECK ON THE EARTH-CARRYING CAPACITY FOR MAN

C. MARCHETTI
International Institute for Applied Systems Analysis, Laxenburg, Austria

(*Received* 25 *October* 1978)

Abstract—Much has been said about the carrying capacity of the earth and with most contradictory results, as the arguments have too often been used in the service of prejudices.

In this paper, we have: made a cross section of a world very heavily populated by present standards; examined with a system view the level of basic necessities plus luxuries for this population; and indicated the technology to satisfy them. Where problems of a global level appeared, a geoengineering solution has been sketched. The result of this analysis is that, from a technological point of view, a trillion people can live beautifully on the earth, for an unlimited time and without exhausting any primary resource and without overloading the environment. The global view of the problems and of their solutions makes the difference and shows that most of the perceived physical limits to growth stem from an inappropriate frame of reference.

Although our result should by no means be interpreted as an invitation to multiply, it does cast some doubt on the reliability of resource investigations within too narrow assumptions about the adaptability of man to changing conditions and transfers the problem of the limits to growth where it belongs: to the areas of sociology, politics, and ethics.

NUMBER OF PERSONS

The figure 10^{12} is based on a somewhat arbitrary maximum density, that of a "garden city" at the level of the globe (see Fig. 1). In practice, the natural trends of a megapolis will push toward zones of much greater densities, leaving the possibility of creating very low density patches of "sanctuaries" where everybody might go when he wished.

High densities such as those found in towns are under heavy criticism nowadays as being vastly inferior to the great open spaces of the country (which in the citizen's ideology should be salvaged but should be maintained with a good infrastructure). This point appears to have escaped the country inhabitants who, since the invention of the city, managed to swarm into it

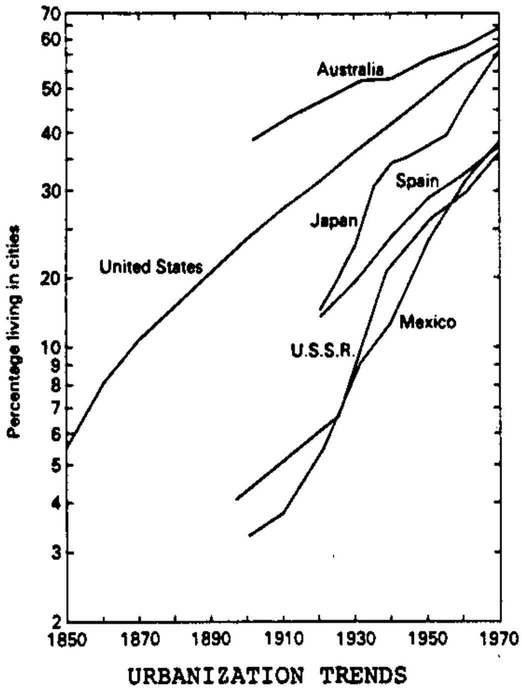

Fig. 1. Urbanization trends in developed countries.

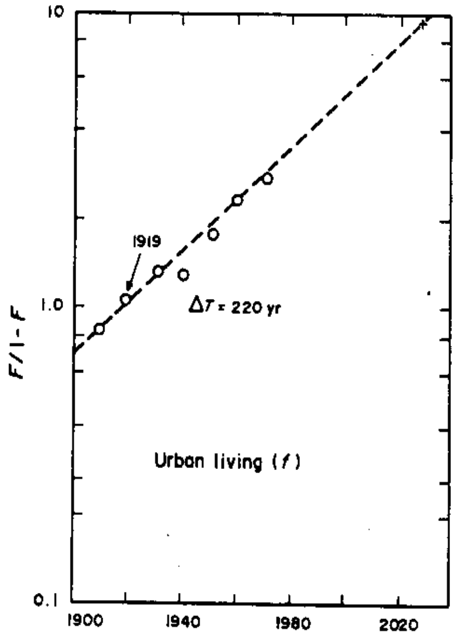

Fig. 2. Urbanization trends in U.S. A logistic analysis. In 1915 the fraction of people living in cities, F is equal to 50%.

whenever possible (see Fig. 2). Is that due only to plain ignorance on their part, or is man naturally a city dweller?

The great drawback of modern cities is that they are never built to the measure of man; they tend to be a patchwork of "machines to live in" where only a limited number of functions is considered essential. Medieval cities may hold the secret of the "human city" where a man will wish to spend all his life; *intricate personal links and beauty* may be the most important components.

Soleri's[1] and Craven's[2] teams have produced very interesting projects, respectively, for land-and sea-based (see Figs. 3–5) cities conceived as tridemsional single units. These

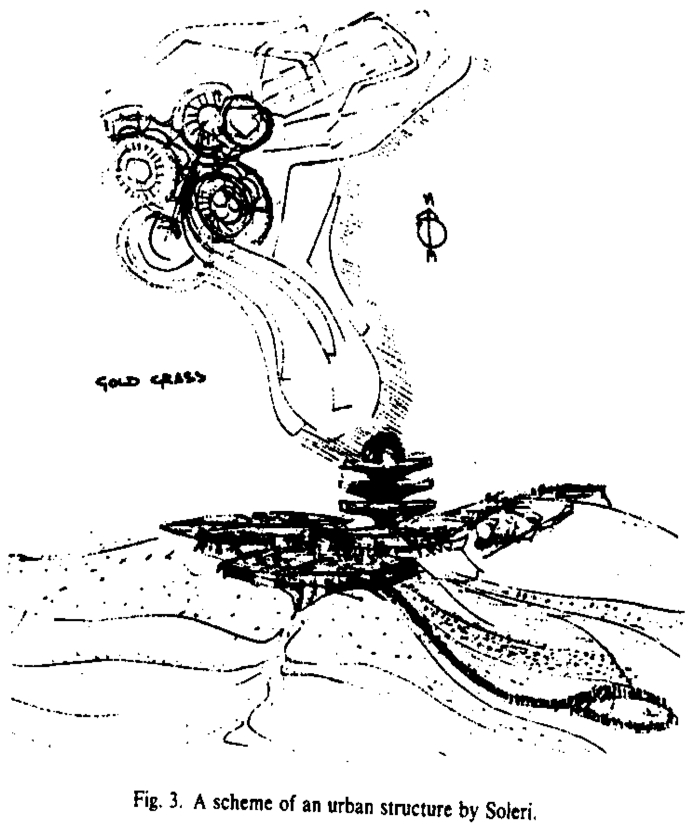

Fig. 3. A scheme of an urban structure by Soleri.

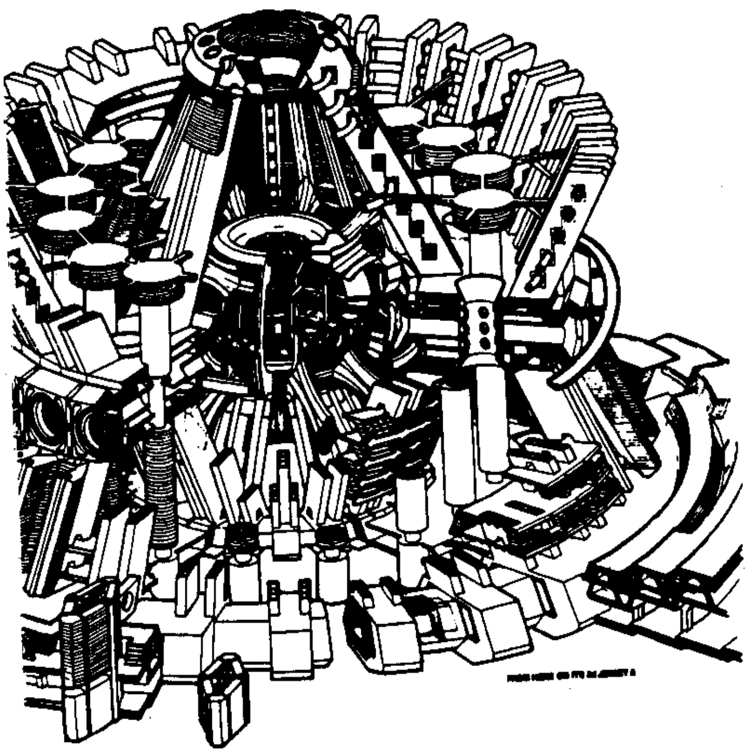

Fig. 4. A scheme of an urban structure by Soleri.

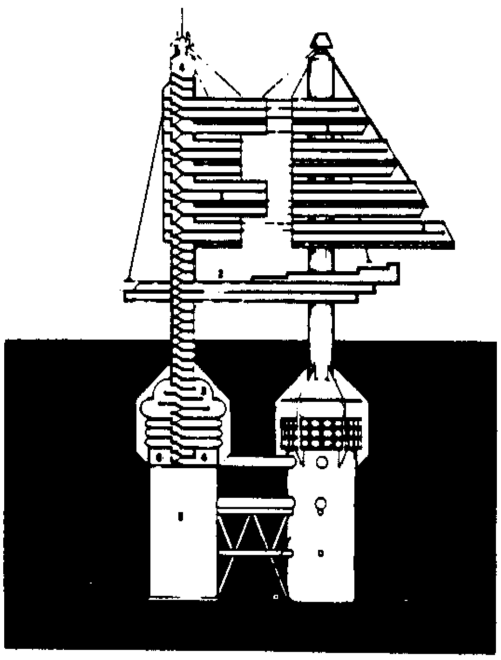

Fig. 5. Scheme of a module for a floating city by Craven.

structures may have positive feedback to the global system; the control of temperature and ventilation via proper control of the radiation coupling with the environment may also serve to control the albedo, which finally limits the amount of usable energy.

DISLOCATION

From the point of view of coverage of the earth surface, the Craven project of cities on floating platforms makes the ocean equivalent to the land. The Craven city should not be more expensive than its equivalent on land, the platform and the supporting "bottles" being gigantic but essentially simple structures with multiple functions.

We feel confident that structurally and functionally a "human city" can be devised. The great size of these agglomerates appears as a major obstacle to the attainment of such a goal, but the hierarchization of the system into units of growing size with some strong intra-unit couplings and some weak(er) inter-unit couplings may solve the problem, as it has done in the past.

These cities, like the Amazonian forest, will be essentially closed systems where most of the materials, including water, will be recycled, the only physical input being free energy and the only output heat. If the input is in the form of negentropy, there will be no output at all. Hence the only factors that must be taken into account from the point of view of the material balance are the "dowry", i.e. the materials locked into the system and the losses in the recycling process.

If we assume for the dowry 100 tons of materials/man, of which 30 tons are "high energy" materials such as metals and organics and 70 tons are "low-energy" materials such as concrete, this will correspond to about 2×10^6 kWh/man for their production, or 40 years of "manufacturing" energy on the basis of our minimum hypothesis for energy available at equilabrium (see the next section). As the buildup of the system may well take 200 years, the ratio appears very reasonable.

ENERGY CONSUMPTION

The amount of energy available is calculated backward from the assumption that the thermal balance of the earth is not modified for reasonable large areas (e.g. 10,000 km^2) and long times (e.g. one month). As the local (and global) thermal balance is controlled essentially by the albedo with respect to the solar radiation, i.e. by the percentage of solar radiation immediately diffused back, and by the emissivity in the longwave IR spectrum, any sizable energy input of nonsolar origin should be balanced by a modification of these two factors.

The albedo of the sea is around 10%, that of cultivated land about 25%; the average input of the sun on the earth's surface is about 200 W/m^2. This means that, by changing the albedo by 10%, a very easy operation with sizeable fraction of the earth surface built-up, we can afford to dissipate 20 W/m^2 or 10 kW/man of nuclear or fossil origin. If part of the incoming solar

Table 1. Vital statistics for a 10^{12} people world.

Dislocation	10% of the earth surface is used on land or sea
Energy consumption	10 kWyr/yr equivalent per person, corresponding to roughly the means of the U.S. and Western European consumption, from nuclear or solar sources [10 kWyr/yr, corresponding to the equivalent of 100 kWyr/yr for 1978 technologies]
Staple food	Included in the energy/biochemical interface
Housing	Cathedral cities; 90% of the earth is left in its natural state
Structural materials	Al, Mg, Fe; [C, Si, Ca, O_2, H_2]
Water	Recycling; make-up from rain
Transportation	Magnetically suspended vehicles in vacuum tunnels will be used for long-distance transportation
Communication	Wired city

Table 2. On the quantity of life (per capita).

Mean income	\$ 10^5 (1978)/year
Apartment space	100 m^2
Distance traveled (Maglev)	10^6 km/year
Computer services	10^{12} bits/sec

radiation that would normally be absorbed is transformed into other forms of energy, e.g. electricity or hydrogen, the thermal balance of the earth will not be affected (Table 4).

The 10 kW correspond to about the present per capita energy consumption in the U.S.A., where, however, the second law efficiency in its use about 5%. Taking into account the natural evolution toward more efficient processes (Fig. 6), we have assumed it to be 50% in the future, i.e. man will get technological benefits equivalent to 100 kW consumed with present technologies.

The figures for the last three entries in Table 5 may seem unbalanced. But long-range transporation is assumed to be by vehicles suspended magnetically in vacuum tunnels and so requiring marginal amounts of energy to be operated; and communication and information processing will be at levels many orders of magnitude above the present ones. The power of 1 kW corresponds to a processing capacity of something of the order of 10^{20} bits/sec, at room temperature. Space conditioning may be done in the good old way, using essentially the

Table 3. On the quality of life.

Informational linkage	→	To every non-private environment
Occupational activity	→	Information processing
Non-occupational activity	→	Physical interaction
Food variety	→	Never eat the same twice

Table 4. The energy envelope.

Solar energy falling on the earth	180×10^3 TW
Solar energy falling on the built-up area	18×10^3 TW
Energy consumed at 10kW/p.c.	10×10^3 TW
Albedo control of the built-up area	$\simeq 10 \times 10^3$ TW

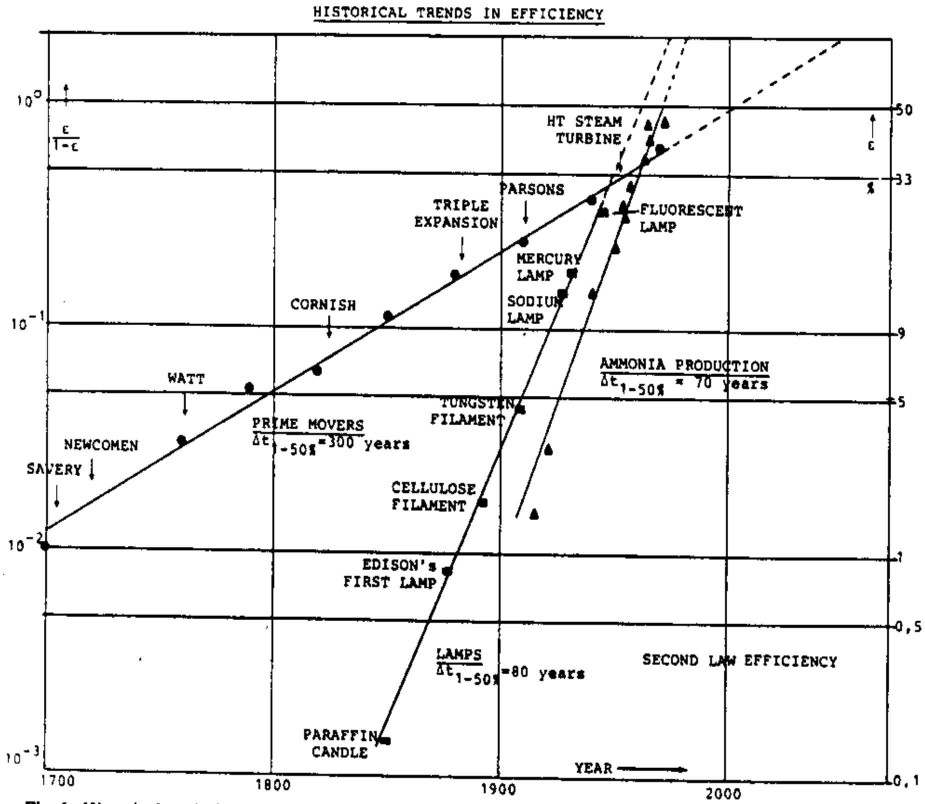

Fig. 6. Historical evolution of efficiency ϵ for three technologies. Δt is the time for efficiency to go from 1% to 50%.

Table 5. Breakdown of per capita energy consumption.

Manufacturing	6 kW
Transportation	2 kW
Communication	1 kW
Space-conditioning	1 kW

sun and ingenuity to drive the system. Lighting is included in this block, but clever ways can be devised to store solar light, e.g. in liquids "pumped" by solar radiation and discharged by electric stimulation.

As our system is imagined as stationary, manufacturing will be essentially geared to maintenance and substitution. The 6 kW/man may correspond to 1 ton/yr of aluminum or magnesium. The production of food may require 0.5 kW, 5% of the total energy budget or 10% of the budget for manufacturing, a non-negligible but not a major fraction.

From the point of view of procurement, there seem to be no problems: e.g. uranium in the sea amounts to about 4.5×10^9 tons, corresponding for roughly 10^{20} kWh. This corresponds to 10^3 years for our 10^{12} men at 10^5 kWh/yr. As the cooling water of a nuclear power plant located on the sea carries about ten times the amount of uranium fissioned in the plant, this source already appears accessible with breeder reactors.

But this just scratches energy reserves. In fact, the minimum energy per nucleon in an atomic nucleus corresponds to the elements in the center of the periodic table (Fig. 7). The fact that we have just started nibbling at the edges is due to the relative ease of the corresponding nuclear transformations. But most of the elements can be used as nuclear fuels, conceptually, and the means will certainly be available in time. The capacity of profitably transmuting any element may also indicate the final solution for radioactive waste disposal.

Our system being homogeneously distributed over the surface of the earth, no particular problems of waste heat disposal may occur once the above condition of radiative energy balance is respected.

It must be remembered that our starting hypothesis—that the albedo is changed by ten percent only (out of the 70% available), and that solar energy is not really included in the budget—is on the conservative side. So perhaps a budget of up to 50 kW/man may be feasible.

STAPLE FOOD

While talking about arable lands and irrigation schemes is the staple job of many respectable people, a simple analysis shows that this game cannot go very far. However, simple analysis from slightly wider point of view shows that the master clutch between the sun and the

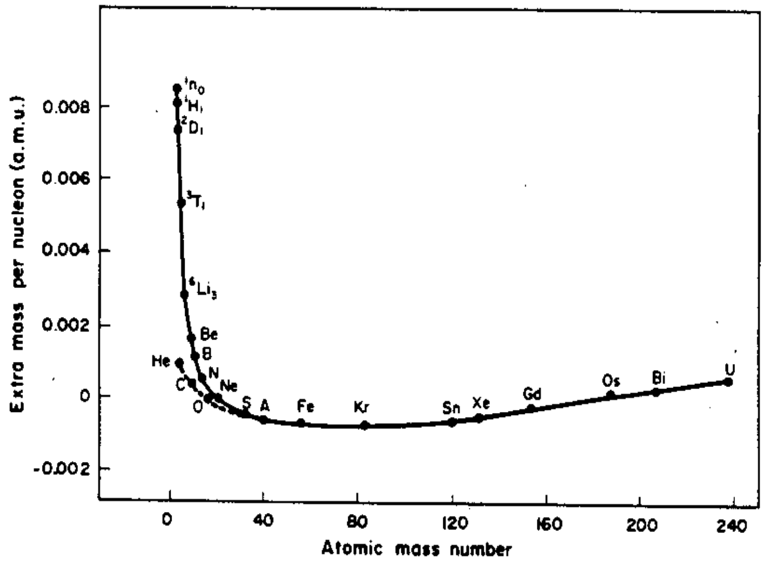

Fig. 7. Nuclear extramass of the elements.

biosphere operates the trivial process of the breaking water up into hydrogen and oxygen, hydrogen being the energy vector to the biosphere.

The answer to the question whether hydrogen produced in other ways can perform a similar task is affirmative. The implications are clearly of revolutionary importance.

The simplest way of doing the trick is through microorganisms capable of using hydrogen as a reductant. These microorganisms are in fact very common and are under intensive study, because they permit the production of proteins, fats, and other chemicals using a completely inorganic substrate (CO_2, ammonia, phosphorous, iron salts, etc.).

The mean energy input of a man is about 100 watts. The efficiency of the microorganisms can be between 50% and 70%, and between 50% and 90% for transforming primary energy into hydrogen. So we transformed these 100 watts into the 500 indicated in the energy budget for manufacturing, to take account of all the inefficiencies. Half a kW is then the amount of primary energy we earmark for the production of biosynthetic food.

The techniques that made it possible to produce such a splendid variety of wines and cheeses out of two insipid fluids can be deployed to reproduce the miracle.

The indoor growing of fancy foods such as capers or blackberries that is starting now may develop into a frenzy. A "wall-paper" of strawberries may give the owner great aesthetic rewards—and the thrill of searching for food in the wilderness—the year round.

Some conventional agriculture can be kept for the aesthetic enjoyment of flowers and wines, and forests may provide materials for the microbiological transformers. After all primary productivity in forests today is in the range of 100 TW, or the level of food consumption of our 10^{12} population.

Table 6. A possible pathway to produce biosynthetic food.

Primary energy source	Nuclear
Intermediate process ——→ H_2 ——→	Microorganisms
Chemistry of final product	A la carte
Texturing of final product	Through processing

STRUCTURAL MATERIALS

All projections put great stress on this point, easily demonstrating that present reserves of copper, nickel, chromium, etc., will run out in the year 2021. But the rational way to set the problem is to stress the functions and then go back to the materials suitable to perform these functions.

To stay on the safe side, we suggest using as "staple materials" elements whose availability on the surface of the earth crust or from sea water can be considered as practically infinite. As an example clay, an exceedingly common material, can contain 30% Al_2O_3, 65% SiO_2, 5% Fe_2O_3 (expressed in equivalent form); and Mg contained in the sea amounts to 10^{15} tons or 10^3 tons/man in our 10^{12} scenario.

The reason why these large resources are not used at present is that the economics of their exploitation are marginally inferior to those of high-grade ores. But development is going on and could be fostered in view of long-range objectives—e.g. to develop processes consuming an amount of energy double the theoretical minimum, with a certain disregard for the level of capital investiment. After all, a 10^{12} population with an income of the order of (1977) \$$10^5$ per capita, in a static system, energy limited, may have some problems in placing their savings. A great potential lies in old but upgradable materials, e.g. stones. Foamed glass can be an emblematic case.

The amount of material to make up the "dowry" of the system (10^{15} tons, or about 10^6 km^3 of original material, or a cube with sides of 100 km) is really negligible amount on the geological scale. It may be considered almost a byproduct of landscaping.

Carbon compounds may constitute the backbone of sophisticated materials (biological systems give a striking spectrum of the potential). The source of carbon can be atmospheric CO_2; the sea buffer; byproduct CO_2 in the production of metals from carbonates (e.g. $MgCO_3$); and coal and oil deposits. After all, humanity now extracts about 5×10^9 tons of carbon (coal

Table 7. The materials endowment, per capita.

Metals	25 tons
Non-metals	70 tons
Organics	5 tons
Mg in sea water	10^{12}x10^{3} tons

and oil) per year, and reserves of reduced carbonaceous materials are well in the 10^{12} ton range, or one ton/man in the 10^{12} hypothesis. One can visualize the "dowry" in organics in the range of 5 tons/man, out of the 30 tons earmarked as metals and organics. Silicon can play a parallel role.

A non-negligible amount of carbon will circulate via the metabolism of this human population, about 200 g/man/day or $0.2 \times 10^3 \times 10^{12} = 200$ million tons/day, more or less what we burn now during one month. To this corresponds a metabolic power of 100 TW, somewhat striking if referred to humanity, but the same ball park of the present metabolism of land plants.

HOUSING

The conceptual structure of the city has not essentially changed from Babylonian times: a two-dimensional grid of communication (information) plus transportation lines (the streets), linking a set of living, working, and social places. The fact that energy is carried by electric cables or carts of logs is immaterial from the point of view of the conceptual structure of the system. The same is true when we use skyscrapers: the two essential functions, communication and transportation, are still operated on a two-dimensional grid.

The potential solutions offered by modern technology for construction, ventilation, lighting, transportation, and communication make feasible huge, truly three-dimensional structures, *cathedral cities*, capable of containing millions of people. The Arcologies of Soleri and the floating version of Craven give a hint of the future (Figs. 3–5). The necessity of building towns

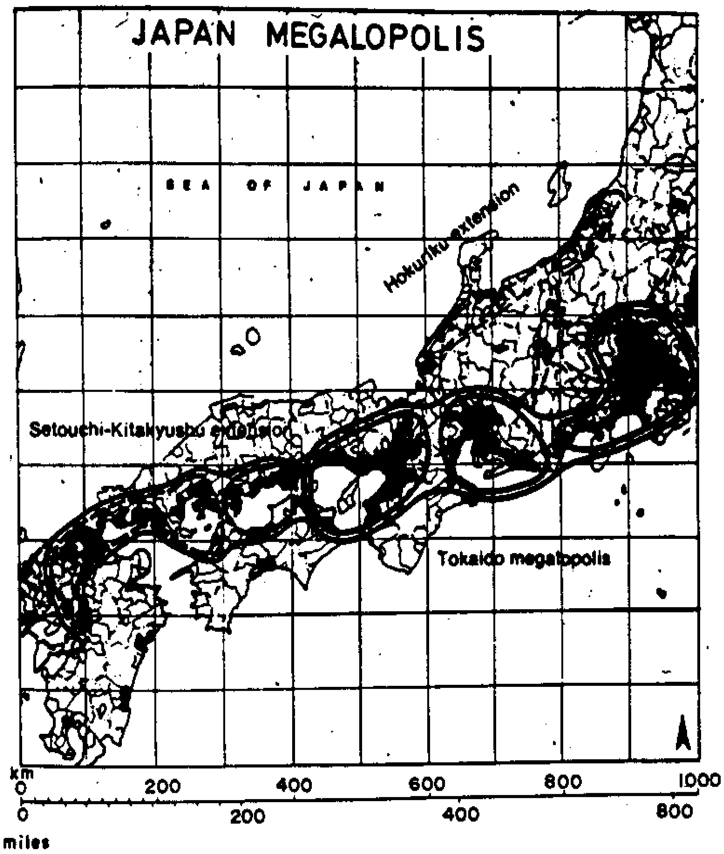

Fig. 8. A megalopolis in formation—The Tokaido megalopolis (From Fig. 5).

on the sea in places where the hinterland of existing cities is already choked (e.g. Hong Kong, Tokyo) may provide the proper ecological niche for realizing the ideas of Craven and Soleri and for their evolution into vital (and reproducing) systems.

The medieval city solved the problem of human interaction in a dense system, and the problem of separation from nature, by reconstructing nature sublimated in art. Modern technology may project the scale by two to three orders of magnitude by reducing the characteristic transit times in like measure.

The attainable densities fit the figures of our hypothesis reasonably well—we visualize 10% of the globe built-up (Figs. 8 and 9), all the rest being left wild—as do the materials and energy necessary to build and run these structures.

As the studies of the Craven team show, there is no essential difference between land and sea for siting one of Soleri's Arcologies.

WATER

Water is fluid of life and much poetry has been poured over it. A free-living cell may require 1000 times its volume in water as its "Lebensraum"; a cell in our body is satisfied with $\frac{1}{10}$ its volume in water: the magic word "recycling" makes the difference. This image parallels those of savage man drinking at the brook (and fighting for it), and of town dwellers whose water comes back in tighter and tighter circles.

The water for our megalopolis or ecumenopolis may come essentially from recycling, perhaps with some hierarchy to satisfy aesthetics. But as we assume a density of one man/500 m^2, rain, at the present level, may provide a fresh input of about one ton of water/man/day: an excellent value even at the level of present consumption.

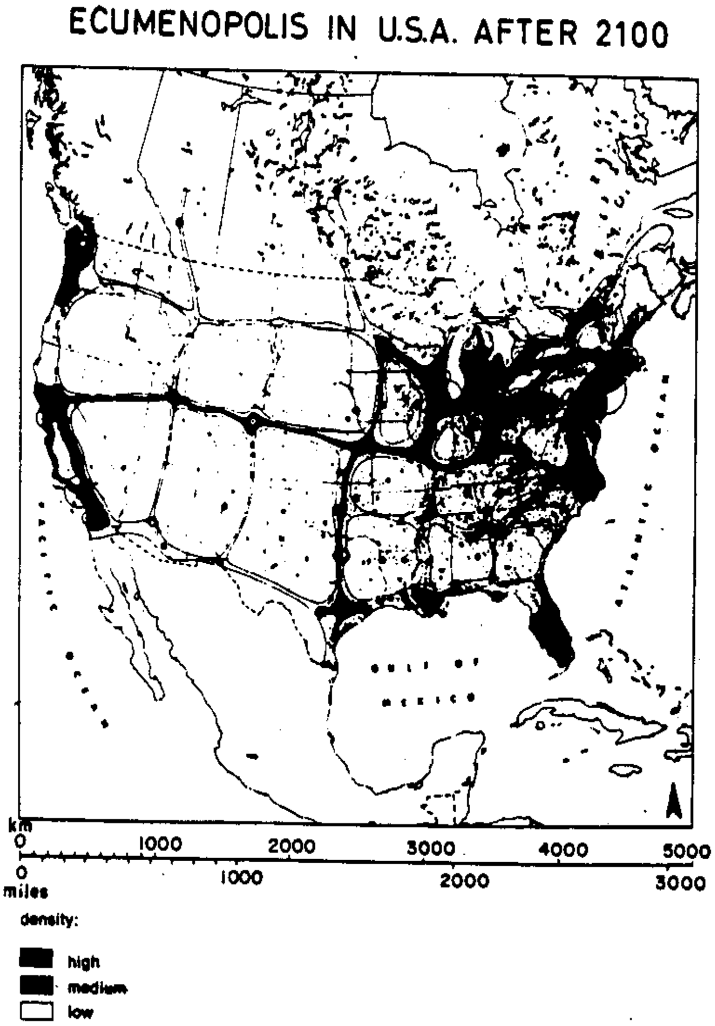

Fig. 9. Ecumenopolis in formation. Population patterns for the U.S.(From Fig. 5).

With our assumption of 50% thermodynamics efficiency for all processes, "compressing out" impurities to recycle water requires very small amounts of energy. Dialytic membranes pave the way to such very efficient purification systems. So in the absence of agriculture, large-scale desalination does not appear to be a global necessity, and we do not give it a place in our energy budget. As hydrogen will probably be, with electricity, the main energy carrier, its combustion may provide another important source of water, let us say 200 l./man/day, at the level of final consumers.

COMMUNICATION

Information processing and transport are *the* core of our civilization, much more than the steam engine (or energy) as many people still think at the back of their mind. After all, the energy available per productive worker is today just an order of magnitude larger than for a medieval worker.

Information will be almost all in a 10^{12} people world, because:

The different levels of hierarchy of organization will require internal processing for running the hardware and the software of the system.

The amount of information available as software of the civilization will have reached enormous levels. Actually it doubles every ten years for science alone, and no saturation is in sight.

Each person will require a multipurpose high-level link (supervideophone) to every other person, to any place in the system defined as public, and to the hierarchical information stores, even if only a small fraction of the information carried is actually used. After all, the eye is a narrow-angle, high-resolution, random scanner picking only the plum of what is available.

The extraordinary number of bits/sec we allocated to each person, requires highly efficient information manipulating equipment. A computer processing core has now an efficiency, second law, in the order of 10^{-11}. The DNA duplicating system has an efficiency of about 0.1!

Clearly the system will be essentially wired, a solution that has evolved in all higher organisms.

TRANSPORTATION

People and materials are now transported by vechicles that move within a fluid, dissipating most of the energy used to propel them. The necessary breakthrough to reduce this energy is to run the vehicles into evacuated tubes or tunnels. The evacuated space being expensive, it will be advantageous for this and other reasons to run the vehicles at high speed. Above 500 km/kh, wheels are not very suitable, and the various systems of magnetic suspension under development may provide the final, i.e. nondissipative, solution. This may arrive through very strong permanent magnets or high-temperature superconductors, or perhaps in other ways. Such a system (a prototype is under very active development in Japan) has little limitation in speed and can have an enormous productivity (ton × km/hr).

However, it is very difficult to forecast the transportation needs of a system coagulated in clusters of 10^7 to 10^8 men, where materials are recycled, energy is produced locally, and high-level information transport and processing will make, in most cases, people travel a luxury and materials transportation marginal.

Intracity movements, on the contrary, will probably be very intensive, and this will account for most of the energy budget we have dedicated to transportation.

The three-dimensional city, e.g. as conceived by Soleri, through an appropriate space-function hierarchization, leaves much room for sheer walking as the main form of personal and light goods transportation.

Movements of fluids is essentially included under conditioning.

CONCLUSIONS

Glancing at the key problems of the 10^{12} scenario, it appears that the carrying capacity of the earth is not overloaded if a set of conceptually very simple solutions is adopted.

The quality of life taken as a reference is that of the very rich now, plus facilities technology has not provided yet.

The impact of man's presence, and the consequent disruptions are kept to a minimum, essentially via a withdrawal of man from land resources. His coupling with the earth biosphere will be practically nil.

It seems that the problems of growth are basically of cultural character. The Judeo-Christian axiom that the earth is given to man to be dominated, very material to western aggressive and destructive attitudes, may progressively be substituted by the Buddhistic axiom that the earth is given to man to be contemplated. Thanks to an enlightened use of technology.

REFERENCES

1. P. Soleri, *Arcology—The City in the Image of Man.* MIT Press, Cambridge, Mass. (1969).
2. J. P. Craven, Hawaii's Floating City Development Program, *First Ann. Rep*, Fiscal Year 1972, published jointly by the University of Hawaii and the Oceanic Insitiute, 31 August, 1972.
3. R. H. Pry, Forecasting the Diffusion of Technology; *Rep.* 73*CRD*220, General Electric Company, Corporate Research and Development, Schenectady New York, Technical Information Series, (1973).
4. K. Davis, The evolution of western industrial cities. In *Cities: Their Origin, Growth and Human Impact.* W. H. Freeman, San Francisco (1973).
5. C. A. Doxiadis and J. G. Papaionnou, *Ecumenopolis: The Inevitable City of the Future.* Norton, New York (1974).