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HUMAN ECOLOGY ON SPACESHIP EARTH

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1.0 INTRODUCTION

The search for useful energy by human population of the world may be regarded as one of the constants of recorded history. Another historical constant is the desire for national populations to live together in a clean and safe environment until they are threatened by other national populations when even more energy is needed. A third constant is the irreversible path of development of better ways to generate the supply of energy needed to make societal life safer and more comfortable. This continuous quest for abundant energy may be expressed in three axioms that describe the constancy of discoveries that allow people to do better rather than doing without. The three axioms examined here are as follows:

1. At any given growth rate of the population, total energy consumption will grow at greater rate.
2. Fundamental human goals include both the desire for abundant energy on demand and a clean and safe environment.
3. The future of humanity will continue to follow a one-way and irreversible path.

The conclusion drawn from this examination is that until a more useful higher-specific-energy source than controlled nuclear fission is discovered (such as controlled nuclear fusion), nuclear power eventually will become the preferred energy source for the world's population.

1.01 Axiom 1

Humans have, for comfort, ease, and profit, progressed historically through a series of increasingly efficient (higher specific) energy sources—from humans (self, family, slaves, employees) through animals (oxen, camels, horses) to machines (water, steam, electricity, radiation)—at a continuously increasing rate of consumption of energy per unit of "useful" work. It follows, therefore, that at any given growth rate of human population, total energy consumption will grow at a greater rate.

The rate of change in the population of the world has accelerated continuously through human history. Figure 1-1 shows the history of world population over the 2-million-year period from the Old Stone Age through modern times [1]. This figure emphasizes the rapid acceleration in growth over geologic time that started after the plague epidemic in the Dark Ages.

A more modern history (a picture of long-term world population growth from A.D. 0 projected to 2050) is shown in Figure 1-2, using data compiled by the United Nations [2]. Here the rapid acceleration starts from the time of the Industrial Revolution.

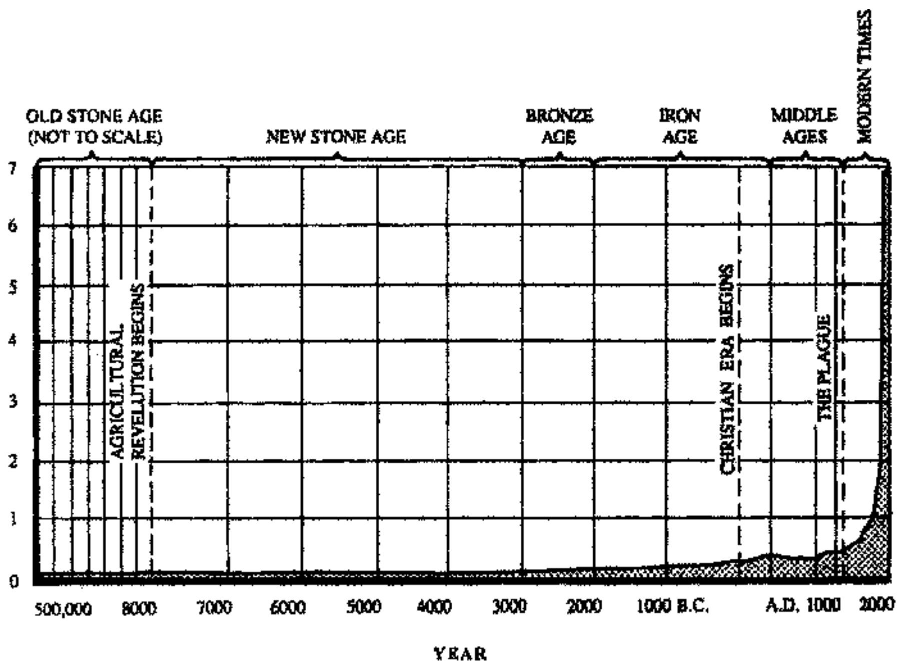

Figure 1-1. Two-million-year geologic history of world population [1].

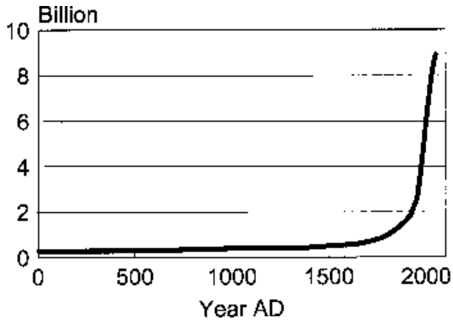

Figure 1-2. Long-term world population growth from 0 A.D., projected to 2050 [2].

The most recent period of history, from 1750 projected to A.D. 2050 by the United Nations [3], is shown in Figure 1-3. The projection shows a decline in annual increments from more than 80 million people per year in the 1980s to fewer than 40 million people per year by 2050. With this steep rate of decline, the world population is expected to reach 9 billion people in 2050 from a population of 6 billion people in 2000.

The acceleration in population growth can be noted from United Nations [2] data in Table 1-1 that show the time interval needed to

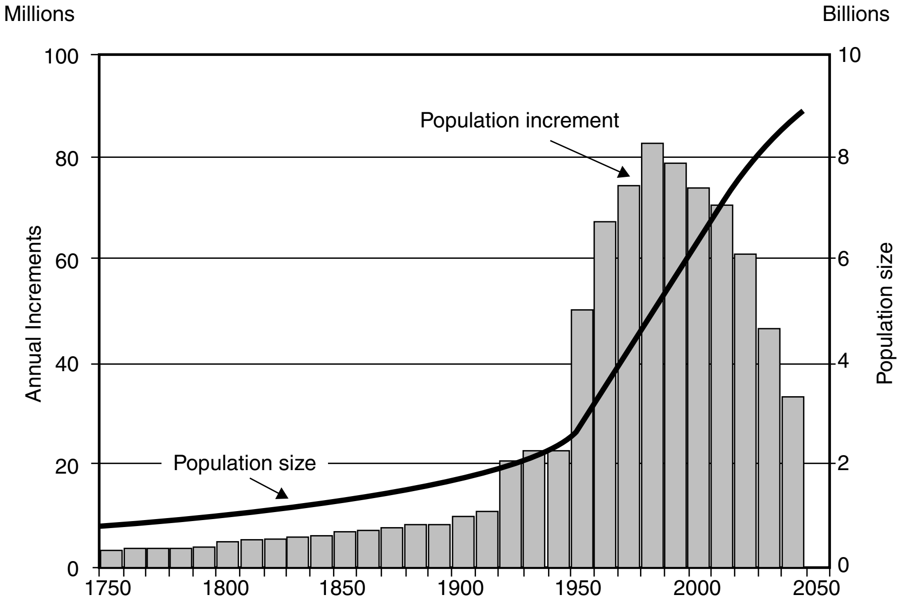

Figure 1-3. World population growth from 1750, projected to 2050 [3].

Table 1-1 Acceleration of world population growth [2]

World Population (Billions)	Year Achieved (A.D.)	Time to Add Last Billion (Years)
1	1804	—
2	1927	123
3	1960	33
4	1974	14
5	1987	13
6	1999	12
7	2013	14
8	2028	15
9	2054	26

increase the population by 1 billion people starting from 1 billion in the year 1804. The lower part of the table shows the deceleration expected by the United Nations on the basis of the declining annual rate projected through 2050.

The corresponding increase in energy consumption as the population has grown can be observed over the geologic and modern time periods. Table 1-2 lists the data for the geologic time period, compiled by Fowler [4] and the United Nations [2]. The population from 5000 B.C. through A.D. 2000 is given in billions with the mean annual growth rate (m.a.g.r.) in percent per annum (%/a) for each successive time period. The energy consumption data are given in kilowatt-hours per capita per day, also with the mean annual growth rate per successive period. The value of 2.9 kWh/cap-day corresponds to the basal metabolism of 2500 kilocalories per capita per day assumed to be needed by prehistoric people.

Table 1-3 lists the world energy consumption per capita for the modern period from 1900 to 2000. The population data are from the United

Table 1-2 Growth in energy consumption from prehistoric times [4]

Period (Date)	Population (Billions)	m.a.g.r. (%/a)	Energy Consumption (kWh/cap-day)	m.a.g.r. (%/a)
300000 B.C.			2.9	—
100000			5.0	<0.001
5000	~0.1	—	9.4	<0.001
0 A.D.	0.3	~0.04		
1850	1.3	0.08	12.0	0.004
1980	4.4	0.94	51.0	1.1
2000	6.0	1.6	230	7.5

Table 1-3 World energy intensity 1900–2000

Year	Energy (Quads)	Population (Billions)	Intensity (MBtu/cap)
1900	22	1.65	13.3
2000	400	6.05	66.1
Increase	18×	3.6×	5×

Nations [2], and the energy consumption data are from the Energy Information Agency of the U.S. Department of Energy [5]. The energy units are given in quads (10^{15} Btu), and the calculated energy intensity is given in million Btu per capita (MBtu/cap). These energy units are reviewed in Chapter 2. The significant observation is the fivefold increase in energy intensity with an 18-fold increase in energy consumption compared with a 3.6-fold increase in population over the twentieth century.

1.02 Axiom 2

Fundamental human goals include the desire for (1) a *pleasant habitat,* defined here as a clean and safe environment, and (2) a life of *comfort and ease,* defined here as abundant energy on demand.

Axiom 2 implies that everyone is an "environmentalist." Most people on earth understand that work (the expenditure of energy) is required to build and maintain a *pleasant habitat* that includes food, shelter, clothing, and the other physical necessities of life. Most people also understand that they do not have to work at all times, that there must be times of rest for *comfort and ease* to enjoy the spiritual aspects of life, such as art, music, and the society of families and other individuals. Most people understand that a pleasant habitat is a clean and safe habitat and expend the energy needed to keep it that way. They generally do this in the context of a life of maximum comfort and ease by reducing personal toil to a minimum (e.g., the energy expended to earn enough for the basic necessities and to maintain physical fitness at a perceived standard). This reduction in personal toil is seen clearly in the rapid adoption of labor-saving inventions such as chain saws, microwave ovens, and electric toothbrushes.

People in large numbers have additional needs for a clean and safe environment. These groups include communities, industry, government, and regulatatory agencies, each of which requires a common expenditure of additional energy. The community congregation of people is illustrated with data from the U.S. census of 1970 on population density in Table 1-4. The table shows that more than 50% of the population lived in fewer than 100 cities. The 1970 census also shows that about 20% of the population lived in 0.1% of the area of the United States.

The trend toward community congregation over a human generation (approximately 25 years) can be estimated by comparing the U.S. census data in Table 1-4 for 1970 with the same data for the year 2000. This is left for the reader to do as a "deeper-look" exercise.

The human quest for abundant and clean energy can be illustrated by the sequence of rapid changes in preferred fuels from before the Industrial Revolution. This quest has been noted by Cannon [6] in a table titled "Moving away from Carbon toward Lighter Fuels" and is expressed in Table 1-5 as the carbon/hydrogen (C/H) ratio. The steep decline from 90% to 0% is shown in Figure 1-4.

1.03 Axiom 3

The history (and future) of humanity follows a one-way and irreversible path.

This axiom implies that civilization as we know it today was developing continuously as the population of the planet increased slowly and remained a small fraction of the sustainable carrying capacity of the earth. The axiom thus is somewhat difficult to defend in that occasional severe events such as wars and disease epidemics have not stopped the growth of civilization by greatly affecting the growth rate of world population. The axiom might be defended by suggesting that there are not enough caves in the world for today's population to revert back to a caveman form of civilization. The possibility does exist, however, for a major fraction of the earth's population to be decimated through a war with "modern technology" (e.g., warfare with weapons of mass destruction) or by a disease that spreads rapidly without means

Table 1-4 U.S. population density in metropolitan areas 1970–2000

Metropolitan Size Range	Number of Cities		Population (10^6)		Population (%)	
	1970	2000	1970	2000	1970	2000
$> 1.0 \times 10^6$	27		68.7		33.7	
5.0×10^5–1.0×10^6	31		22.1		10.8	
2.5×10^5–5.0×10^6	39		13.7		6.7	
Total	97		103.5		51.2	
Total population			204.0	274.6		

Table 1-5 The trend in the C/H ratio in fuels

Fuel	Physical State	Atom % Carbon	Atom % Hydrogen	C/H Ratio
Wood (dry)	Solid	90	10	9.00
Coal (mean)	Solid	62	38	1.63
Oil (mean)	Liquid	36	64	0.56
Octane (C_8H_{18})	Liquid	31	69	0.44
Methane (CH_4)	Gas	20	80	0.25
Hydrogen (H_2)	Gas	0	100	0.00

of controlling it. Even then, if only a few people had to start over they would not have to start from "scratch" in rebuilding the irreversible path of civilization as long as the technical literature remained available.

The technical aspect of the history of humanity is more readily discernible. The development of energy utilization through science and engineering followed a well-established path during the advance of civilization from the discovery of fire and the wheel to the discovery of fission of uranium isotopes and fusion of hydrogen isotopes. An inherent problem in human nature is the almost simultaneous application of each new energy discovery to both civil and military objectives. The history of warfare has been well described (e.g., by Coblentz [7]) and is not considered here. Progress in the development in energy resources also has been described. A convenient way to summarize the history of changes in energy from original solar energy to nuclear energy is shown in Figure 1-5.

The specific energy of fuel, which can be defined as the amount of energy available from a fuel per unit amount of fuel mass (e.g., Btu/

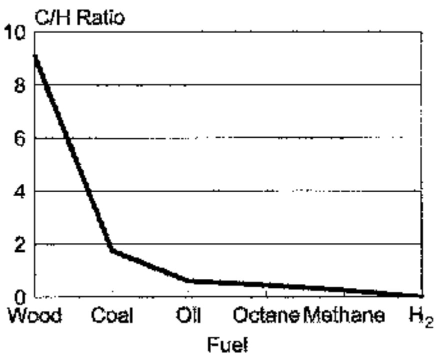

Figure 1-4. The quest for clean fuel as seen in the trend in the C/H ratio.

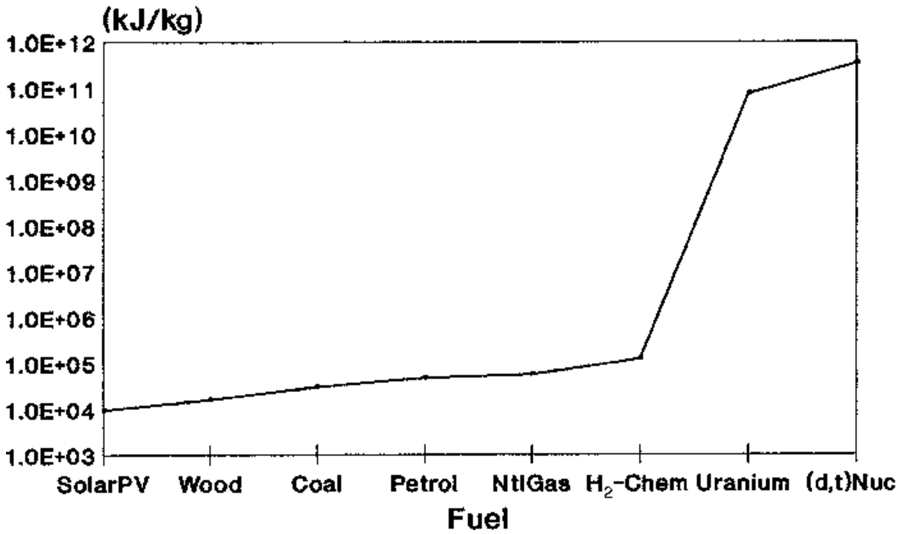

Figure 1-5. The historical sequence of energy utilization as a function of specific energy.

lb in the English system or kilojoules per kilogram in the metric system) is an indicator of the comfort and ease of using a particular fuel. Before fire was discovered, energy on earth was primarily in the form of the heat of the sun and thermal effluents from geothermal and volcanic sources. Unfortunately, the heat of the sun is, by area, too small and diffuse for industrial applications other than providing us daylight for vision, wind power for transportation, and photosynthesis for food production. The solar energy value shown in Figure 1-5 is for solar photovoltaic energy extracted with silicon semiconductor materials that convert solar energy directly to electricity. It has almost the specific energy of wood, which became the fuel of choice when fire was discovered.

The succession of combustible fuels from coal through ‘‘chemical’’ hydrogen shows the increase in specific energy as the choice of fuel changed in accordance with availability. The discovery of nuclear fission energy in the last century provided a choice of fuel about 1 million times greater in specific energy. That power and its introduction as a military weapon have made fission an unpopular choice among a large proportion of the world’s population, especially in the case of uranium (and plutonium) fission reactors. The general popularity of thermonuclear fusion as an energy resource is undetermined since its availability (other than as the "hydrogen bomb") has not been achieved in civilian power reactors. However, the ultimate energy resource that could be available, based on today's technical knowledge, is "solar energy on earth," the thermonuclear energy of the sun, which provides the world with its original and continuous energy, using isotopes of hydrogen in properly engineered power stations.

1.04 Philosophical Questions for the Quest

If we accept the three axioms in the human quest for abundant energy, we can wonder whether we are losing our way in this quest. Will energy consumption continue to grow at a greater rate than population, especially if, as forecast by demographers, the rate of population growth will decline over the next 50 years? Will people abandon the goals of a clean and safe environment if the price of dwindling energy resources continues to increase? Will human history continue along its irreversible path?

These questions lead to a central technology question: As human population in cities, nations, and the world continues to grow, even at a declining rate, should we try to reverse the quest for greater specific-fuel-energy technology? These questions also lead to a central social question: As population continues to grow, do we regress (do without) or do we advance (do better)? It is hoped that as we go through the science and engineering of the quest for abundant energy in these pages, some light will be shed on these questions.

1.1 DEVELOPMENT OF HUMAN ECOLOGY

Energy is a fundamental requirement for the sustenance of life. It plays a key role in the development of the earth's flora and fauna, which are termed collectively the biosphere. Obviously, it plays a key role in human ecology, being one of the major factors that govern the well-being of humanity.

The major factors in the long-term growth of civilization can be grouped into the 5 P's, as follows:

1. *Population.* Population drives the need for sustenance; it requires the development of technical means of providing a food supply in the form of agriculture and livestock.

2. *Population density.* Aggregation of populations (communities) drives the need for engineered environments (buildings, roads, bridges, traffic lights) in the form of cities, states, and nations.
3. *Production.* Large populations, with division of labor, drive the need for manufactured product, measured in affluence, in the form of gross domestic product, the total value of goods produced, and productivity (the amount produced per capita per unit time).
4. *Power.* Power is the time rate of doing work (measured e.g., by horsepower [HP] in the English system or kilowatts [kW] in the metric system) that satisfies the need for abundant energy to achieve a desired objective (e.g., driving an automobile at 100 miles per hour or lighting The Strip in Las Vegas).
5. *Pollution.* Pollution, the aftermath of human endeavors, drives the need for a clean, safe habitat; this reflects the importance attached to the health of the biosphere.

1.11 Major Ages in Human History

Figure 1-1 showed the geologic history of world population over the last 2 million years, starting with the Stone Age. Major developments in human history can be associated with the geologic eras, covering long time periods in the early eras and relatively short time periods in the later eras. A summary of significant periods in human history appears in Table 1-6.

1.12 The Biosphere: "Spaceship Earth"

A simple conception of the biosphere is that it is a single, interconnected diversified system for "life on earth." Life on earth depends on the transformation of some of the sun's radiant energy ($h\nu$) that reaches

Table 1-6 Major ages in human history

Age	Period	Significance
Stone	Prehistoric	Food gathering and hunting
Fire	Prehistoric	Separation of humans from animals
Neolithic	B.C.	Long-term growth of civilization
Urban	Dark Ages	Transport and storage of food: cities
Industrial	Eighteenth century	Transfer to mechanical energy
Technological	Twentieth century	Electronics and nuclear power
Future		Solar energy on earth?

the planet into the chemical energy of hydrocarbons through photosynthesis of chlorophyll by the general reaction

$$CO_2 + H_2O + h\nu \rightarrow C_xH_yO_z + O_2 \tag{1.1}$$

leading to the two major food chain paths. The concept is summarized by the parallel flowpaths

$$[\text{Sun}] \rightarrow \begin{bmatrix} \text{photosynthesis} \\ \text{of} \\ \text{chlorophyll} \end{bmatrix} \begin{matrix} \nearrow [\text{marine algae}] \searrow \\ \\ \searrow [\text{vegetation}] \nearrow \end{matrix} [\text{producers}] \rightarrow [\text{consumers}]$$

The concepts of Spaceship Earth and the food chain are described in an early review of the sustainability of resources by the National Academy of Sciences [8]. Chapter 1 by Bates discusses the human ecosystem (Spaceship Earth).

The two major food chains are the aquatic and terrestrial pathways, with producer through consumer components generalized as follows:

Aquatic (marine algae)
phytoplankton ⇒ zooplankton ⇒ small fish ⇒ large fish

Terrestrial (vegetation)
plants ⇒ herbivores ⇒ carnivores ⇒ parasites ⇒ . . .

These components come into a quasi-equilibrium by the processes of energy flows and material cycling over long periods of time.

Ricker [8] describes the aquatic food chain (“food from the sea”) as a complex pyramid of trophic levels of producers and consumers, as shown in Figure 1-6. Hendricks [8] describes the terrestrial food chain (“food from the land”). A parallel question of *who eats whom* shows for plants such as herbs, grasses, and shrubs several first-order consumers such as insects, crustaceans, and herbivores, with recycling decomposers of bacteria and fungi.

1.13 Limits to Growth

The concept of limits to growth sometimes is stated as the rules that “what goes up must come down” and “there is no free lunch.” Large-scale worldwide concern about the growth of population, the sustainability of natural resources, and the human impact on the environment

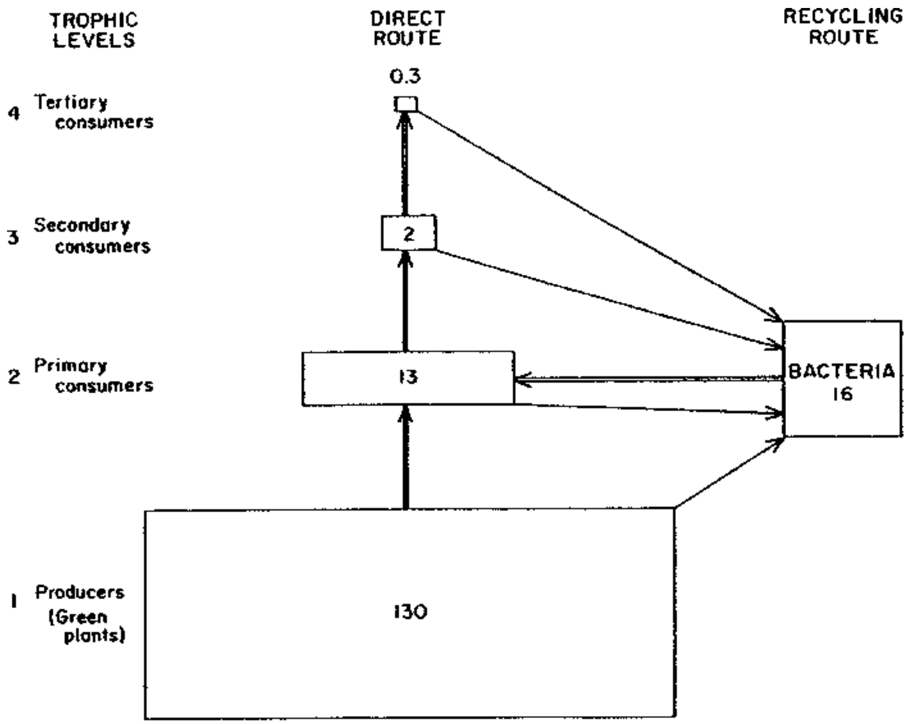

Figure 1-6. The aquatic food pyramid: consumption, production, recycling. From Ricker [8]. Original caption: Simplified aquatic food pyramid, illustrating direct and "recycling" routes for conversion of plant material into animal tissue. Areas of the rectangles are proportioned to the estimated production (*not* the standing crop) of material at each trophic level; production figures are in billion of metric tons of organic matter per year.

may be considered to have started in the social upheavals in the 1960s, but the literature has many references from ancient times. Genesis 1: 28 says, "Be fruitful and multiply, and replenish the Earth, and subdue it." Many lively classroom discussions result from attempts to interpret that quote. In 1798, Thomas Malthus wrote about population as it affects the future improvement of humankind. The revised (and enlarged) revision in 1803 [9] included three key observations:

Population is necessarily limited by the means of subsistence.

Population invariably increases when the means of subsistence increase unless this is prevented by very powerful checks.

These checks, and the checks that repress the superior power of population and keep its effects on a level with means of subsistence are all resolvable into moral restraint, vice, and misery.

Many lively discussions, especially in engineering classrooms, result from attempts to interpret the terms "very powerful checks" and "moral restraint, vice, and misery." Are moral restraint and vice limited to human beings? Does misery (e.g., disease, starvation) affect all creatures?

A large volume of literature on limits to growth developed by the 1970s, as exemplified by the Club of Rome report [10] on the predicament of humankind published in 1972. The major conclusion of the report was, "If the present growth trends in world population, industrialization, pollution, food production, and resource depletion continue unchanged, the limits to growth on this planet will be reached sometime within the next one hundred years. The most probable result will be a rather sudden and uncontrollable decline in both population and industrial capacity (pp. 23–24)." The report provides two solutions to the consequences of its major conclusion: (1) "It is possible to alter these growth trends and to establish a condition of ecological and economic stability that is sustainable far into the future. The state of global equilibrium could be designed so that the basic material needs of each person on earth are satisfied and each person has an equal opportunity to realize his individual human potential." and (2) "If the world's people decide to strive for this second outcome rather than for the first, the sooner they begin working to attain it, the greater will be their chances of success." An update of this book was published in 2004 [11], 32 years later, that discusses some of the processes implied in the first book that are in progress.

As a final example of concern about world survival, the book by Yoda [12] on the world's "trilemma" points out the interrelations between economic development, resources of food and energy, and environmental impacts. The structure of the trilemma is illustrated in Figure 1-7.

1.2 SUMMARY

This chapter made the case that a time in human history has arrived that shows that continued growth in human population, with concomitant greater growth in energy demand, may not be sustainable far into the future. World population is expected to grow from 6 billion in 2000 to about 9 billion by 2050 if the forecast of an annually decreasing growth rate is met. If it is not, world population could grow at the present annual rate and reach 10 to 12 billion people. It was realized in the second half of the twentieth century that limits to growth exist

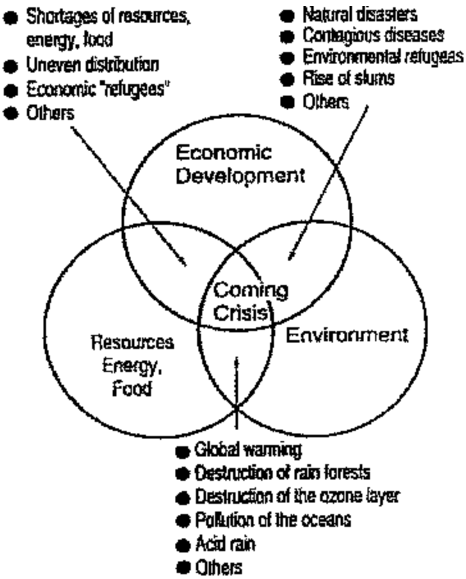

Figure 1-7. Structure of the trilemma: the three major problems threatening world survival. From Yoda [12].

and that if growth continues at current rates, severe problems in the sustainability of needed resources (e.g., energy) could become acute. The following chapters attempt to examine the growth of energy consumption, the sustainability of energy supply, the long-term energy resources available, and the resulting environmental impacts caused on global and local scales, all of which affect the human quest for abundant energy.

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