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Fusion Energy Conversion

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Foreword

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Norman H. Jacobson
Manager, ANS Publications

D-T fuel would provide a unique 14-MeV source, whereas D-D fuel would result in a dominant 2.45-MeV flux.*

The design of a system explicitly for commercial irradiations would involve two primary considerations: First, the incorporation of irradiation facilities would require a special blanket design; second, an optimum neutron flux would require careful selection of the type of reactor and the plasma conditions. Irradiation facilities would possibly consist of sample ports and/or flow tubes in the blanket. Of principal concern would be the maintenance of adequate neutron economy for tritium breeding (if required) and the use of structural materials that avoid premature neutron damage† but that are compatible with the chemicals or other substances being irradiated. The selection of an optimum reactor for irradiation is much more complicated and involves a number of factors. However, some aspects of the dependence of the neutron flux on the type of reactor and plasma conditions can be illustrated through a simple model.

Consider an idealized cylindrical plasma of radius r_p operating with a duty factor ξ. Then with D-T fuel, the 14-MeV neutron flux $\phi\,[\mathrm{n}/(\mathrm{cm}^2\ \mathrm{sec})]$ at the vacuum wall (radius r_w) is simply

$$\phi = \tfrac{1}{8}\, n^2 \langle\sigma v\rangle_{\mathrm{DT}}\, r_p y \xi \ , \qquad (6.1)$$

where y is the plasma-to-wall radius ratio r_p/r_w. Figure 6.1 presents a plot of this relation and shows the expected operating regions for various types of reactors.[1] Mirror reactors are quite attractive for this purpose since they offer large fluxes with relatively small, steady-state reactors.[2,3] Laser-pellet and theta-pinch reactors could also give large average fluxes if high pulse repetition rates, i.e., high ξ, are achieved.[4] Because of their relatively low power density, low-β toroidal systems generally offer lower neutron fluxes but over a larger useful irradiation volume. However, as stressed by Jassby,[5] two-component tokamak reactors (see Chap. 2) are especially attractive as a neutron source since they offer a maximum power density. Jassby[6] also suggests a novel colliding-beam design for high fluxes.

6-1.2 Plasma Energy Extraction

To avoid contaminating the reactor chamber regions, the plasma energy would probably be extracted via the exhaust from an open-type reactor or from the divertor of a closed-type reactor. This approach, proposed by Eastlund and Gough[7] in connection with the *fusion-torch* concept for reclaiming basic elements from solid wastes, is illustrated in Fig. 6.2.

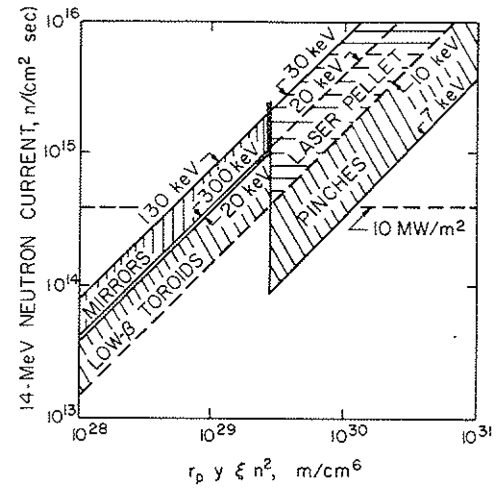

Fig. 6.1. Neutron current at the first wall of an idealized cylindrical D-T reactor (from Forsen[1]). The reactor is characterized by the product of the square of the plasma density ($n^2 \cdot \mathrm{cm}^{-6}$), plasma radius ($r_p$ - m), ratio of plasma to wall radius (y), and duty cycle (ξ). Uniform density and temperature are assumed across the plasma. For mirror reactors, a mirror ratio of 3.3 is used. The duty factor ξ represents the fusion burn time divided by the time between pulses. Thus, $\xi = 1$ for steady-state operation, but values of $\sim 10^{-2}$ are typical of designs such as the theta-pinch reactor of Fig. 4.14. The low ξ values represent a key obstacle that may prevent pulsed-laser and theta-pinch devices from achieving the operational levels suggested in the figure.

The plasma generated in region I is transferred to region III, the interaction zone, via region II, the connecting region. The 90-deg turn indicated is accomplished by appropriate magnetic fields and serves to isolate region III from neutrons generated in the reactor. By the time the plasma reaches region III, its density and temperature are sufficiently reduced to quench further fusion reactions. Solids or other materials being processed would be vaporized and ionized by injection directly into the plasma in this region. Flow and pressure gradients would be selected such that the backdiffusion of the process material into the fusion reactor would be held to tolerable limits.

The requirement that the plasma must transport sufficient energy to vaporize the injected particles in an efficient manner would determine the temperature and density conditions in the

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*Due to side reactions and the burning of fusion products, some neutrons at both energies will be involved, but a single energy can be emphasized by carefully selecting the plasma conditions (see Chap. 2).

†With the fluxes involved, eventual radiation damage seems inevitable; consequently, replaceable sections and remote handling capability appear mandatory.

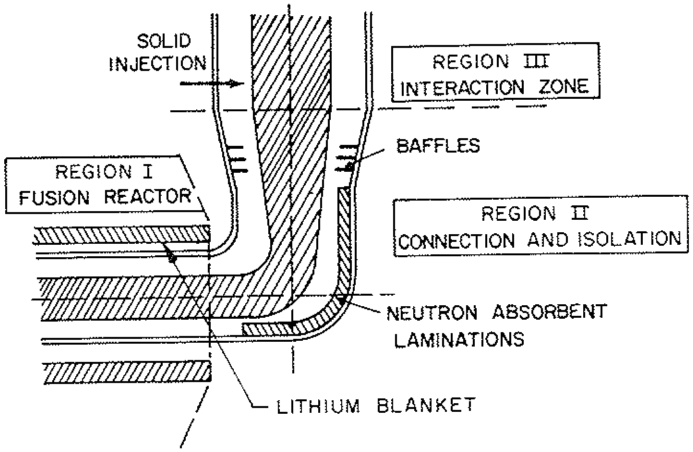

Fig. 6.2. Fusion-torch concept (from Eastlund and Gough[7]).

interaction region. Eastlund and Gough[7] define this requirement as follows:

The energy flux F [J/(cm^2 sec)] transported by a plasma of temperature T and density n is approximately

$$F = 2nkT(kT/2\Pi m_e)^{1/2} \quad . \tag{6.2}$$

Shock heating is desired for fast evaporation to avoid ablative cooling. To propagate a shock wave, it is necessary that

$$F > v_s E_v \quad , \tag{6.3}$$

where v_s is the shock speed in the solid and E_v is the vaporization energy per unit volume (typically 10^5 cm/sec and 10^4 J/cm^3, respectively). In addition, sufficient energy must be supplied to vaporize the pellet in a time that is shorter than the shock-wave transit time. This leads to

$$\frac{1}{v_s} > 1.3 \times 10^3 \, rE_v^2/nT^{9/2} \quad , \tag{6.4}$$

where T is in keV, r is radius of the solid particle in cm, and the other symbols are as previously defined.

These relations are summarized in Fig. 6.3 where solid pellets of 1-cm radius are assumed. Quite high densities and/or temperatures are required for shock evaporization; for example, a typical density of 10^{14} ion/cm^3, temperatures >30 keV are indicated. It may not be practical to maintain such severe conditions in an exhaust region; therefore, ablative evaporation might be used if the resonance time in the interaction zone is adequate. As seen by extrapolation of Fig. 6.3, ablative evaporation might use more modest conditions such as 10^{13} ion/cm^3 and 6 keV. Nevertheless, an energy flux of 10^7 J/(cm^2 sec) is required, some three orders of magnitude larger than that obtained in conventional dc arc devices.*

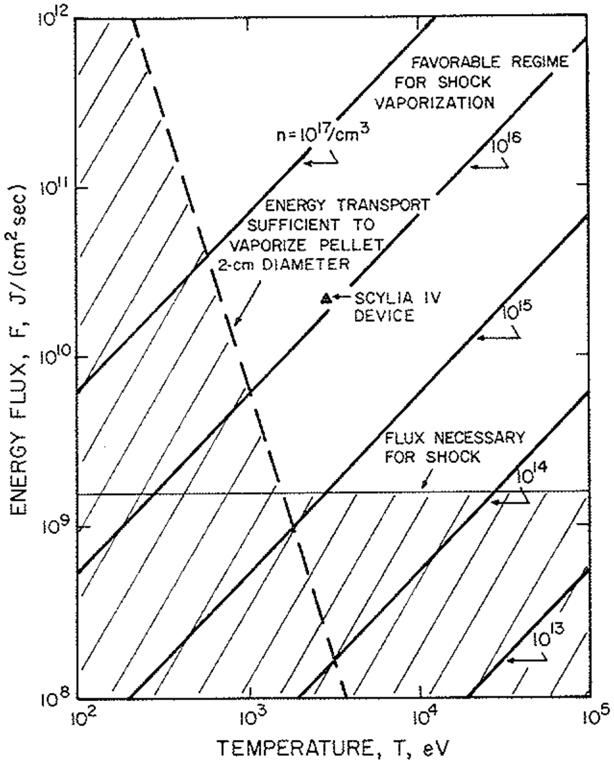

Fig. 6.3. Requirements for shock vaporization in the interaction region of a fusion torch (from Eastlund and Gough[7]). Shock vaporization is favored in the unhatched region in the upper right; ablation dominates elsewhere.

6-1.3 Radiation Extraction

While the fusion plasma itself provides an intense radiation source in the x-ray (bremsstrahlung) and infrared (cyclotron)

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*It has been difficult to vaporize solids in such arcs because of a short residence time in the hot portion of the arc and the relatively low energy flux.[7]

ranges, these radiations are easily absorbed in structural materials. Thus, it would be difficult to design a first wall that would transmit the radiation and simultaneously meet the strength and cooling requirements imposed on the blanket. To avoid this problem, the exhaust plasma might be used in a manner analogous to the fusion torch[7,8] illustrated in Fig. 6.4. The wall surrounding the exhaust faces less stringent conditions than does the blanket wall, possibly making a "transparent window" region feasible. This also opens the possibility of injecting materials to enhance radiation production and tailor the

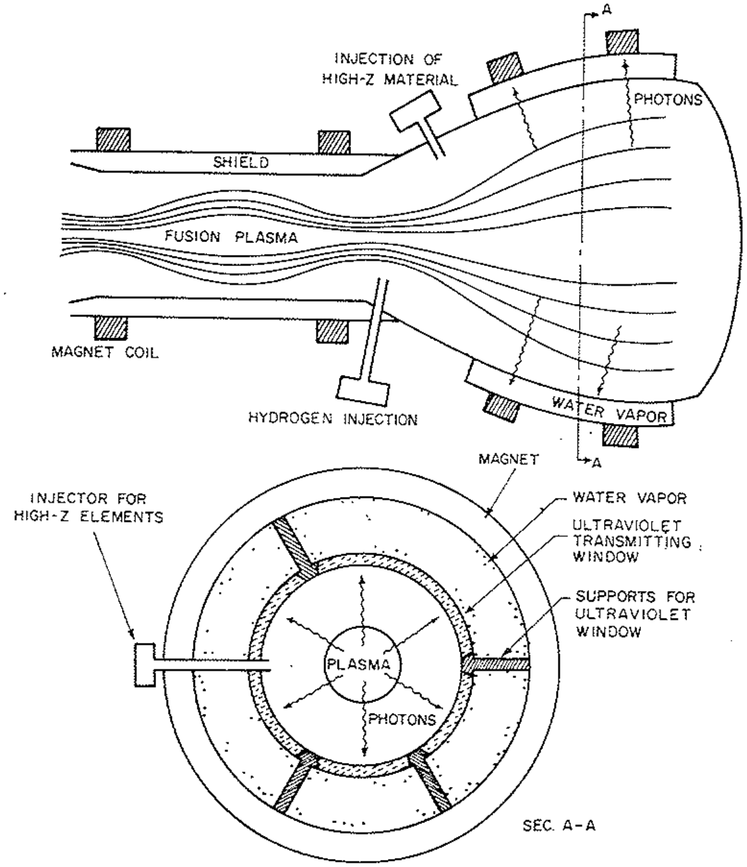

Fig. 6.4. High-Z material injection into an exhaust plasma to obtain enhanced radiation for a process unit (from Eastlund and Gough[8]).

wavelength to a range desired. For example, Eastlund and Gough[8] suggest that the injection of aluminum could convert up to 85% of the plasma energy into ultraviolet (uv) radiation between 1800 and 1950Å.*

The impurity radiation arises from three major processes: (a) bremsstrahlung, (b) line or excitation radiation, and (c) recombination radiation. The relative importance of each depends on the type of impurity and the plasma conditions.

Hopkins[9] finds that the radiated power density P due to an impurity of atomic number Z is approximately

$$P = n_e n_i^* Z^3 \sum_{j=0}^{2} K_{j+1} (T_e/Z^2)^{1/2-j} \ (\mathrm{W/cm^3}) \ , \qquad (6.5)$$

where T_e is the electron temperature (°K), n_e and n_i^* are the electron and impurity ion densities ($\mathrm{cm^{-3}}$), and K_{j+1} are characteristic constants; for example, for carbon, $K_1 = 4.8 \times 10^{-31}$, $K_2 = 1.82 \times 10^{-32}$, and $K_3 = 4.13 \times 10^{-34}$. A plot of this relation is shown in Fig. 6.5.

Note that $(T_e/Z^2) \gtrsim 10^{-2}$ keV is required for strong line (uv) emission. Thus, for aluminum injection an electron temperature below ~2 keV would be necessary. At intermediate temperatures, a superposition of all three radiations with a corresponding wavelength spread would be obtained. The largest power densities are actually obtained at lower temperatures via line radiation.

In summary, the selection of the impurity, injection rates, and plasma conditions offers considerable control over the radiation emission. Although no firm calculations are available, Table 6.1 presents rough estimates of power splits from a hypothetical 1000-MW D-T reactor.

As indicated, proper design could lead to very intense sources of neutrons, radiation, or plasma energy; for example, the 55- to 75-MW uv source indicated in the table is well beyond any present-day uv source. However, it is clearly difficult to obtain a single energy form. For example, if a D-T reactor were designed to provide a uv radiation, it would still be necessary to utilize the large neutron, x-ray, and plasma flow energies in other ways (electrical production, fissile-fuel breeding, etc.). The use of advanced fuels would offer higher temperatures and increased bremsstrahlung and cyclotron radiation powers.

6-1.4 Energy-Consuming Units (Source Torches)

The preceding remarks assume that a self-sustaining fusion reactor is to be utilized. This is not required, however, if we

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*The resonance lines of Al-II lie in this range.

since they must exploit several unique features of a fusion reactor. Unfortunately, however, little work has been done in this area, so *the discussion must be viewed as highly speculative*.

6-3.1 The Fusion Torch—Materials Processing

The potential for using a fusion reactor to process materials was first highlighted by Eastlund and Gough,[7,39–44] who proposed the "fusion torch" concept as a means of recovering pure elements from waste materials, thereby "closing the cycle from use to reuse."* More recently, Sabri[45] completed an extensive study of the feasibility and safety aspects of a fusion torch.

In a sense, the fusion torch represents a scaled-up version of current electrically powered plasma torches or plasma jets which have already found a variety of commercial applications, including coating and spraying surfaces, spheroidizing and preparing particles, constructing melting furnaces, providing radiation sources, and synthesizing chemicals.[46–50] To illustrate the similarity of proposed fusion-torch schemes, in Fig. 6.11 we show a proposed

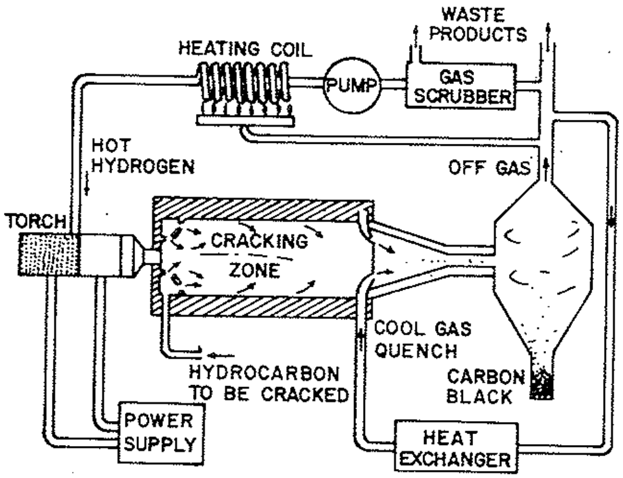

Fig. 6.11. Proposed scheme for cracking hydrocarbons to produce carbon black (from Dennis et al.[47]). Conventional techniques utilize an air fuel and a gas-turbine-type combuster. Aside from economic considerations, the plasma-jet approach holds the promise of creating uniquely shaped particles with more desirable surface conditions.

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*Eastlund and Gough[8] also apply the term "fusion torch" to the radiation-processing unit of Fig. 6.4.

large-scale application of a plasma torch for the production of carbon black. The use of conventional plasma torches for such processes faces several difficulties: First, problems involved in getting energy into the arc have restricted the size to relatively small-scale units; second, while plasma-energy densities are sufficient for melting solids or cracking organic materials, they have generally not been suitable for completely vaporizing and ionizing solids. In contrast, by virtue of obtaining energy directly from the fusion plasma, the fusion torch would allow large flow rates and complete ionization.

In this spirit, Gough and Eastlund[44] define two types of fusion torches. As indicated in Table 6.7, a *source torch* (ST) would employ fusion technology (e.g., high-frequency heating, energy storage methods, etc.) in large-scale electrically driven devices.* On the other hand, the *reactor torch* (RT) uses the exhaust plasma from a fusion reactor as input power. We will concentrate on the RT here.

Three possible RT cycles are illustrated in Fig. 6.12. In scheme A, the solid is simply injected into the exhaust plasma, and the various components are then separated. In this scheme, the temperature and density of the plasma are not easily controlled. Thus, in scheme B, a "carrier gas" is injected prior to the solid. Part of the plasma energy is transferred to the gas, thereby permitting some control over the conditions prior to the injection of the solid. In both approaches, however, the solid comes in direct contact with the fusion fuel and ash; this may introduce problems, particularly if tritium remains with the product streams because of imperfect separation. To avoid this contamination, the fuel and ash could be separated from the carrier gas prior to the injection of the solid (scheme C). The use of a gas such as argon or N_2 with a larger mass than the fuel makes the separation relatively simple and efficient; however, this advantage would be at the expense of energy losses associated with the mixing with and the heating of the carrier gas.

With the large capital investment in the fusion reactor and torch, the RT would be limited to processes involving large-volume high-income products. Three such applications can be envisioned now: (a) treatment of wastes, (b) ore reduction and purification, and (c) select chemical synthesis. The practicality of such operations ultimately depends on the technical success of

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*As discussed in Sec. 6-1.4, the ST concept might also be applied to a low-Q (driven) fusion device.

TABLE 6.7

Torch Concepts

Device	Input Energy	Gas	Plasma Temperature (°K)	Density (cm^{-3})
Plasma torch	High-frequency rf, μ wave, or electrical discharge	Arbitrary, typically H_2, N_2, Ar, or air	10^3 to 10^4	Low-pressure discharges at 10^8 to 10^{12}; high pressure arcs at 10^{16} to 10^{19} (partially ionized)
Source torch	Scaled-up version of the above, using fusion technology	Extension of above	---	---
Reactor torch	Fusion, possibly with supplemental electrical input	D-T or other fusion fuel, possibly with diluent	10^6 to 10^9	10^{13} to 10^{16} (fully ionized)

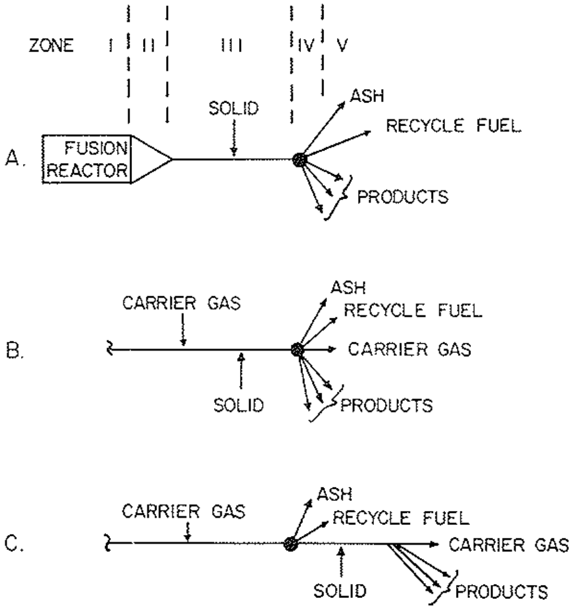

Fig. 6.12. Possible reactor-torch cycles. Various zones are indicated: I.—fusion reactor; II.—connection; III.—interaction; IV.—separation; V.—product and recycle fuel. Another alternative (see Fig. 6.4) would be to use the torch as a radiation source. The injected solid or gas would then be selected to provide radiation in the desired wavelength region.

the torch concept itself, the suitability of processes with high-income products, and the seriousness of the radioactive contamination of products. Since a detailed study is not yet available, subsequent sections are restricted to some general observations.

Technical feasibility is best examined by considering some problems associated with each region shown in Fig. 6.2. The *connection zone* (region II) serves to connect the reactor to the interaction zone by providing a flow path for the exhaust plasma. Conversely, it is imperative to prevent impurities from diffusing back into the reactor. This is to be accomplished by using baffles or other structures to condense backscattered elements and by maintaining a large bulk-plasma flow velocity. Some laboratory data suggest[7,51] that this is possible on a small scale, but the practicality for commercial processes remains an open question.

The connection region must also shield the interaction zone from neutrons from the reactor in order to avoid activating the products. As illustrated in Fig. 6.2, this might be accomplished by a 90-deg turn, using appropriately shaped magnetic fields.

While this seems plausible and some experimental data are available,[7,52] questions of losses, wall heating, etc., must be considered in the context of a large flow rate. Finally, the connection zone must be designed to provide appropriate plasma densities and temperatures in the interaction region. Fusion reactions must be quenched to prevent continued neutron generation; yet the plasma-energy density must be maintained for efficient vaporization. Some experiments[7,53] where a theta-pinch plasma was guided in a mirror field confirm that reasonable flow control is possible, but the question ultimately must be evaluated relative to a given process scheme. For example, if the injection of a carrier gas becomes necessary, questions about mixing, charge exchange, and efficiency must also be evaluated.

The central function of the *interaction zone* (region III), namely the shock vaporization and ionization of the injected pellets, was discussed in some detail in Sec. 6-1.2. For a given solid, appropriate plasma conditions can be specified to achieve the desired vaporization.* The question remains, however, as to whether or not these conditions are compatible with practical reactor design.

Another critical problem centers on the *separation process* (region IV) which must be efficient, yet economical. If even small amounts of impurities remain in the recycle fuel, they could accumulate and seriously degrade reactor operation. If any fuel, particularly tritium, remains with the product, the result could be disastrous.

Eastlund and Gough[7,39] suggest eight potential separation techniques:

1. electromagnetic separation
2. quenching
3. selective recombination
4. charge exchange
5. plasma centrifuge
6. plasma acceleration
7. field curvature
8. quadrupole methods.

However, little study has been devoted to the large-scale utilization of such methods, the only specific study being by Sabri,[45] who considered the use of a plasma centrifuge with a torch. Her findings are favorable, and she concludes that a centrifuge would be suitable for the separation of quite complicated compounds in only a few stages.

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*This problem is closely related to the fueling of reactors by the injection of frozen deuterium pellets and also to the laser-pellet interaction problem.[54-57] Both these areas are receiving increasing attention, and extensive data should soon be available.

In view of the large investment involved in an RT, commercial application would require a large volume product offering a sizable income. The recycling of wastes originally suggested by Eastlund and Gough[7,39] falls into this category but must be viewed as a long-term possibility.

Near-term prospects would seem to center on energy-intensive processes such as aluminum extraction from bauxite. Indeed, considerable effort has been extended to develop a plasma-based process for this[58]; thus far, however, approaches using *electrically* generated plasmas do not appear economically competitive.

6-3.2 The Fusion Torch—Chemical Production

The fusion torch might also be considered for chemical production. For example, instead of solids (cf., Fig. 6.12), methane might be injected and conditions sought to favor the synthesis of acetylene.* Another approach would be to use radiation from the torch to initiate photochemical processes (see Fig. 6.4).+ We will briefly consider each of these approaches.

6-3.2.a Plasma Processing

The use of a fusion torch for chemical processing represents a logical extension of current plasma-chemistry technology.[65-76] To illustrate some possibilities, in Table 6.8 we have listed some chemical reactions that have been studied using laboratory-scale plasma jets and arcs. No detailed studies of possible applications to fusion-torch processing have been reported; therefore, specific reactions of importance remain uncertain. Yet some general observations are possible.

Both the decomposition of compounds or the reverse, i.e., the synthesis of compounds from basic elements, are conceivable. However, *endothermic reactions are favored* since the large heat content of the plasma will drive a reaction such as

$$A + B \rightleftharpoons AB - \text{heat} \quad \text{(endothermic)} \tag{6.8}$$

to the right. In contrast with an exothermic reaction like

$$C + D \rightleftharpoons CD + \text{heat} \quad \text{(exothermic)} \quad , \tag{6.9}$$

the high temperature involved favors the reactants, C and D.

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*Such a process has been carried out commercially in an electrically driven plasma-arc furnace.[59]

+Alternatively, the neutrons or bremsstrahlung from the reactor itself could be used via techniques developed by the USAEC to use radiation from fission reactors or radioisotopes for radiation processing.[60-64]

TABLE 6.8

Some Chemical Reactions Carried Out in Plasma Jets and Arcs

Product	Overall Reaction	Process	Approximate Conversion	Reference
Synthesis Reactions				
Hydrogen cyanide	$2C + H_2 + N_2 \rightarrow 2HCN$	Feed consumable C electrode and H_2 into a N_2 plasma jet	50% C to HCN	67 and 73
Ammonia	$Mg + N_2 \rightarrow MgN_2$ $MgN_2 + 3H_2O \rightarrow 2NH_3 + MgO_3$	Inject powdered Mg into a N_2 plasma jet; extract MgN_2 and decompose in water	40% MgN_2 yield	67 and 74
Acetylene	$2CH_4 \rightarrow C_2H_2 + 3H_2$	Inject CH_4 into Ar plasma jet	Over 80% of CH_4 converted to C_2H_2	67 and 75
Fluorocarbon	$2CF_4 \rightarrow C_2F_4 + 2F_2$	Inject CF_4 into a C arc	Up to 69 mole% C_2F_4 obtained	67 and 76
Decomposition Reactions				
Aluminum	$2Al_2O_3 \rightarrow 4Al + 3O_2$	Inject Al_2O_3 pellets into Ar plasma jet	Low yield	67
Pyrographite, hydrogen	$CH_4 \rightarrow C + 2H_2$	Blow CH_4 onto mandrel heated by plasma jet	Not given	67

Thus, attempts to form ammonia by injecting hydrogen into a nitrogen plasma jet have not been successful[67] since the reaction

$$N_2 + 3H_2 \rightarrow 2NH_3 \qquad (6.10)$$

is exothermic.* Conversely, various reactions leading to nitrogen oxides, such as

$$N_2 + 2O_2 \rightarrow 2NO_2 \quad , \qquad (6.11)$$

are endothermic and have been achieved in a plasma arc.[72]

Plasma chemical processing will typically involve *three basic steps*[65]:

1. production of reactive species via heating of the reactants in the plasma
2. reactions to form free radical intermediates and/or products
3. rapid recombination reactions to form products during quenching to prevent competing reactions.

Since most chemical reactions involve atomic and free radicals (as opposed to ionic species), it is neither a desirable nor an efficient utilization of energy to ionize the reactants fully. Thus, the relatively moderate plasma conditions are desired.

These considerations suggest a flow process such as that illustrated in Fig. 6.13, which is a logical extension of current small-scale plasma units used in manufacturing nitrogen fluoride.[69,70] The fusion exhaust energy is first transferred to a "carrier" gas (either an inert gas or one of the chemical reactants) which is subsequently separated from the fusion fuel and ash. After

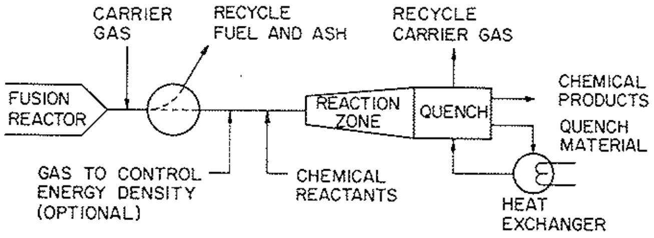

Fig. 6.13. Possible flow scheme for chemical production using the exhaust plasma. To illustrate some possibilities, we assume that nitrogen is used as the carrier gas. Fluorine might be injected at the reaction zone to synthesize nitrogen fluorides,[69,70] or the carrier gas might serve simply to transfer energy; for example, argon might be used and methane injected to synthesize acetylene, as has been done in some argon-plasma-jet studies.[67] Many other combinations are conceivable.

---

*Hydrazine (N_2H_4), which has a negative heat of formation, is generally obtained instead of ammonia.

separation, the carrier gas provides a flowing low-temperature plasma analogous to electrically driven jet and arc plasmas. Its flow rate and the chemical injection rate are selected to provide the desired ionization of the chemicals.

The *reaction zone* in Fig. 6.13 provides conditions that promote the formation of the intermediate free radicals. The temperature is reduced at a rapid rate that favors recombination of the radicals to form the desired products in the quench zone.* Adequate quenching is a key step, and existing small-scale plasma-jet processes typically achieve quench rates of from 10^5 to 10^8 °K/sec using one of three techniques:

1. The plasma is directed onto a cold surface, e.g., water-cooled tubes.
2. The plasma is entrained ("dumped") into a cold, high-density inert gas.
3. The plasma is injected into a cooled fluidized bed, e.g., fluidized alumina pellets which are recirculated through a heat exchanger.

Fast quench rates have also been obtained in large-scale processes employing expansion through a deLaval nozzle.[69]

In summary, the feasibility of chemical production via the fusion torch ultimately rests on such factors as whether appropriate reaction conditions can be achieved and contamination of the products avoided. Furthermore, as discussed relative to the processing of materials (see Sec. 6-3.1), a large-volume high-dollar-value product is essential for commercial utilization. Indeed, the chemical market appears to hold this possibility.

For example, the annual production in 1972 of four major candidates for plasma synthesis—acetylene, fluorocarbons, chlorocarbons, and ammonia—represented a market value of \$3 billion and consumed ~10^{11} kWh of power.[57,71] In contrast, the electrical generating capacity in the United States was ~1.5×10^{12} kWh, which at 6 mill/kWh represents \$9 billion.

6-3.2.b *Photolysis*

We now turn to a second unique approach to chemical production suggested by the fusion-torch concept: *photolysis using uv radiation*. Because of the lack of strong uv sources, research on uv photolysis (<2000 Å) has thus far been quite limited. However, in Table 6.9 we briefly consider the reactions that seem likely candidates[77] for large-scale processes.

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*Otherwise, valuable products may be lost via side reactions or reverse reactions.

TABLE 6.9

Some Potential Ultraviolet Photolysis Applications

(from Daniels[77])

Product	Reaction
Hydrogen	$H_2O \rightarrow H_2 + O_2$
Carbohydrates	$CO_2 + H_2O \rightarrow H_2CO + O_2$
Carbon suboxide	$6CO \rightarrow 2C_3O_2 + O_2$
Ozone	$3O_2 \rightarrow 2O_3$

Because of the potential importance of hydrogen as a basic form for energy transport in the future (the so-called *hydrogen economy*[78-84]), the photolysis of water is a key reaction.* Preliminary experiments have produced H_2 and H_2O_2 by the photolysis of water vapor (at 200 to 350°C and 1.3 to 28 Torr) using a 1849-Å source[8,85]; however, as is shown in Table 6.10, other reactions are theoretically possible. Hydrogen has also been obtained in other studies which used an additional catalyst.[8] It is not clear, however, that this technique can compete economically with conventional electrolysis or with various thermal decomposition methods such as the Mark cycles developed by DeBeni and Marchetti.[79]

Several recent studies[8,86,87] have specifically considered the fusion-torch photolysis method for hydrogen in a preliminary fashion. If 1849-Å photons are produced by injecting aluminum into the torch plasma (cf., Fig. 6.4), the maximum conversion efficiency is ~14%.+ Another approach would be to inject neutral deuterium gas into the torch to produce 1215-Å Lyman-α radiation[86]; this offers a theoretical efficiency about three times higher. It is not clear, however, how close a practical process can approach these limits, one of the major uncertainties being whether or not the product hydrogen can be separated out quickly enough to prevent recombination.

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*Alternatively, a fusion reactor could be used as the primary energy source for electrolysis or thermal processes, but here we are primarily concerned with direct photolysis. Axtmann and Fish[86,87] have also noted two "hybrid" approaches: First, water vapor might be injected directly into the exhaust plasma to achieve radiolysis; second, photons from the plasma torch could be used to illuminate semiconductor electrodes in unconventional electrolysis cells.

+The maximum quantum efficiency (molecules H_2 produced per photon absorbed) for H_2O decomposition at this wavelength is ~0.4.[8,85]

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To the Framers of the
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3.21 THE FUSION TORCH

The fusion torch concept was conceived in 1968[1] and centers around the potential industrial uses of ultra-high temperature plasmas. (Plasmas are gases in which one or more electrons have been removed from the gas atoms.) Such plasmas are available now in experimental devices and could be made available at low cost in large quantity when fusion reactors become a reality.

Man must learn to cooperate with nature (see Section 6.1). This will require the development of new industrial technologies in which energy can be generated and utilized without creating material residues that pollute the environment. The fusion torch concept proposes the use of energy in the form of high-temperature plasmas.[2-9] Energy in such a form may appear as, or can be converted to forms such as, kinetic, ultraviolet, microwave and x-rays that can be tailored to do specific jobs. Figure 3.21a illustrates some possible applications of the fusion torch concept as man moves toward a closed cycle economy with minimum industrial wastes.

The fusion torch concept can be applied in several ways. Its required energy input can be obtained directly from plasma or from an external electrical energy source and the energy it releases can be converted to electromagnetic radiation (UV or x-rays) or to particle kinetic energy.

One application of the fusion torch is to recycle solid wastes. As part of an integrated waste reclaiming facility, plasma recycling could effectively handle the most difficult components of solid waste; and ultimately, plasma recycling could provide a total recycling capability.

A block diagram of how a plasma recycle system would operate is shown in Figure 3.21b. Certain components of presently planned solid waste treatment facilities would fit quite naturally into the overall scheme. Solid wastes would be prepared by shredding, drying and sorting operations. Various presorted combinations would then be injected into the above mentioned ultra-high temperature plasma and vaporized, dissociated and possibly ionized. The resulting mixture of elements could then be separated and recovered.

Research is presently underway to develop techniques of production and control of ultra-high temperature plasmas. In recent years, some experiments on the use of lower-temperature plasmas in ore reduction have been carried out. However, no experimental work has been reported on solid wastes.

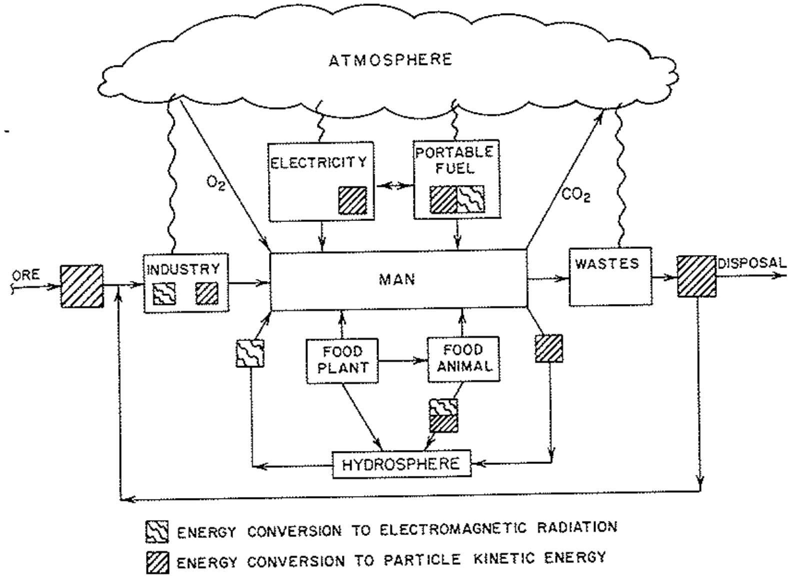


Figure 3.21a Possible applications of the fusion torch.

Description of a Fusion Torch

An operational schematic of a plasma recycle system is shown in Figure 3.21c. The hot plasmas can be confined or held away from the walls of the chamber by a magnetic field. This is because charged particles such as ions or electrons are "attached" to the magnetic field lines and tend to follow these lines. Because of the ultra-high plasma temperature (up to 50,000,000°C), and the resultant high flux of energy in such plasmas, solid particulate matter can be vaporized, dissociated and ionized. One is thus capable of converting the solid, which can consist of any combination of complex compounds, into a relatively simple gas consisting of elements or simpler compounds. The mass of material introduced into the ultra-high temperature plasma cools the gas to a much lower temperature. The fusion torch could convert solids into gases in the 10,000°K to 20,000°K temperature range. This temperature range is compared with the operating temperatures of present day advanced solid waste processing techniques in the lower half of Figure 3.21c. Present day techniques such as pyrolysis are moving toward higher operating temperatures to obtain simple reaction products. The fusion torch thus represents the end point of this trend. Referring again to Figure 3.21b, the separation stage follows the conversion of the solid into a gaseous plasma form. This is the

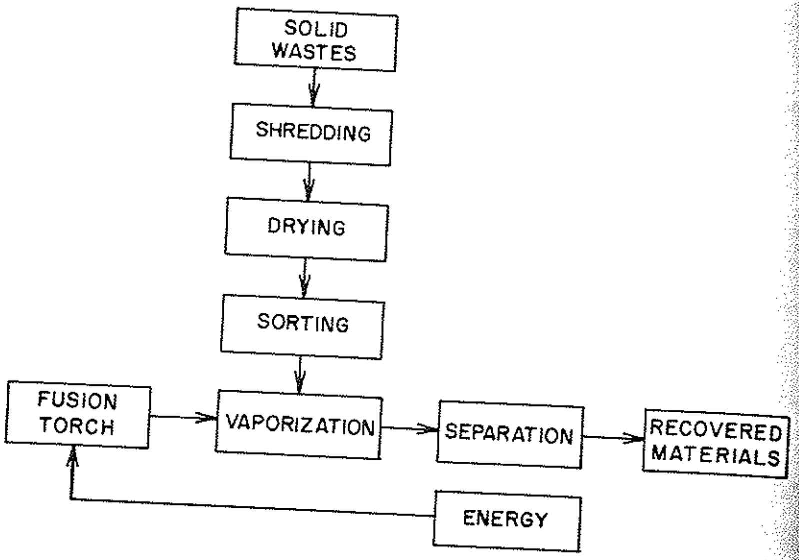
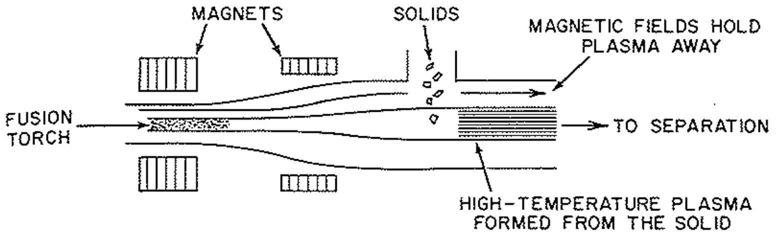


Figure 3.21b Operation of a plasma recycling system.

stage where the individual elements and/or simple gaseous molecules are sorted.

A wide range of possibilities exists for the method of separation to be used. The degree of dissociation or ionization of the gas produced from the solid can be controlled by varying the feed rate of solid particulates and/or by adjusting the power of the plasma source. Thus, basically four gas conditions can be specified at the start of the separation stage. These are illustrated in Figure 3.21d. In stage 1, the solid is converted into a nonionized gas. Stage 2 is the formation of a gas in which all molecules are dissociated. If the initial compounds in the solid are composed of elements with ionization potentials comparable to dissociation energies, then some ionization will also occur. Stage 3 is characterized by ionization of one or more elements, leaving the remainder unionized. Finally, stage 4 involves the complete ionization of the solid.

Stages 1 and 2 do not involve ionization and do not require high-energy inputs. They could be operated by making use of the knowledge already available in the high-temperature chemistry field. For example, "quench" separation techniques could be used. When the temperature of a very hot gas is rapidly lowered, only the simplest molecules will be formed. Thus, for example, the organic components of the solid wastes could be converted into simple hydrocarbon fuels such as methane. A rapid quench of a high-temperature gas can be achieved by such means as injection of cold (liquid N_2) gases,



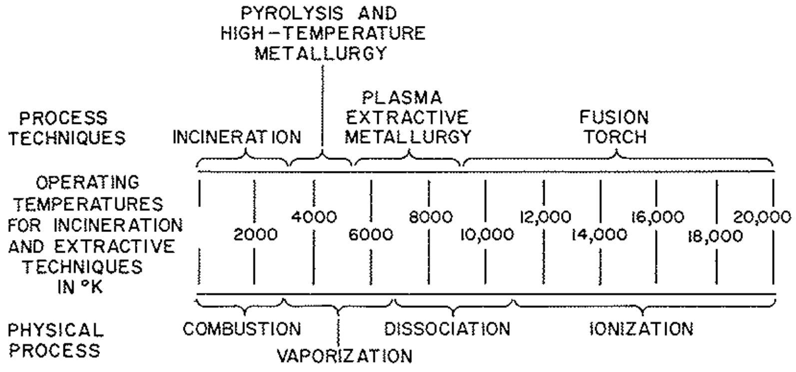


Figure 3.21c Operational schematic of a plasma recycle system.

flowing the gas over cold surfaces or by expansion of the flow streams. Rapid rotation, plasma instabilities, temperature gradients or other thermal effects can lead to separation in flowing gases.

Separation of Ionized Gas Mixtures

After full ionization of a multielement gas mixture, many separation techniques can be considered:

1. Electromagnetic separation involves the use of electric fields to initially separate the ions of different mass and then to collect them in separate boxes. This technique has been used for the separation of isotopes.[10,11] It is very expensive, however, and has not been developed for large-scale use.
2. A quadruple separator[12] would allow only one species to pass through the magnetic field region while others are deflected. Some work has been done in this area.

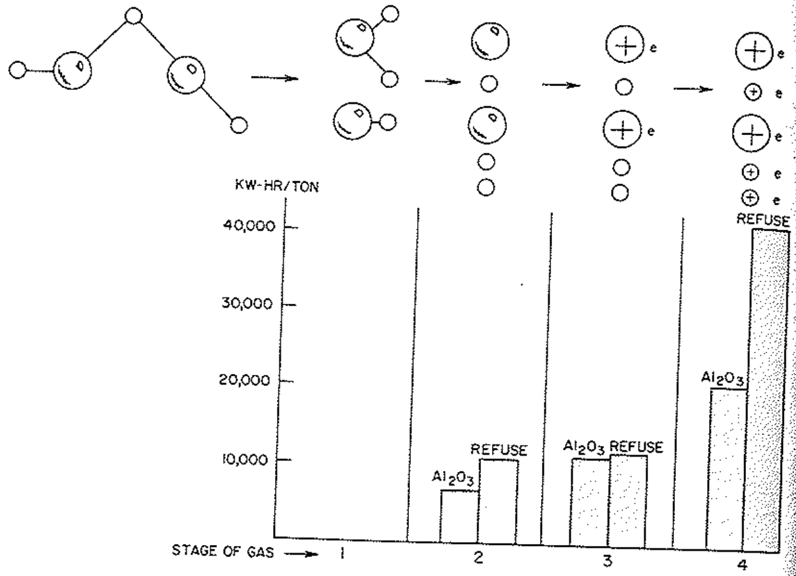


Figure 3.21d Energy required to convert a ton of refuse or a ton of Al_2O_3 into a gas of the type described by stages 1 through 4.

3. The plasma centrifuge would operate similarly to a conventional gas centrifuge except that electric and magnetic fields would be used to produce rotation rates which are much greater than those which can be achieved with normal gases or liquids. This technique has been used to separate hydrogen from argon and hydrogen from deuterium.[13-16]
4. In a plasma accelerator, ions of various masses are accelerated at different angles and could be collected in separate receptacles.[17]
5. Merely flowing a plasma around a curved magnetic field will result in separation of heavy elements from light ones. This effect has been used to prepare pure plasmas at Gulf General Atomic Corporation.[18]
6. When selective recombination effects are utilized the plasma flow stream is brought to a set of conditions in which a particular species would recombine and leave the plasma while the others remain "hooked" to the magnetic fields and are piped away along these fields.[2]
7. Charge exchange effects could also be used, in which a neutral atomic species replaces a plasma ion in the flowing plasma to selectively remove a material. The replaced plasma particle could be collected on the walls as a neutral atom while the remaining species are piped away.[2]
8. Other ideas such as combinations of traveling waves in the plasmas and use of particular plasma resonances have been suggested but have not been explored in depth. These techniques could be combined with previously discussed methods to enhance separation.

When low ionization potential species are preferentially ionized (stage 3) both chemical separation and plasma separation techniques could be utilized. The ionized species would be constrained as a plasma by the magnetic field lines while the unionized species could be absorbed on wall elements or pumped away by vacuum pumps.

Collection of separated species can occur in a number of ways. For example, metallic elements could be condensed on cold surfaces which intersect the flow stream of ionized or vaporized metals, while gaseous species could be pumped into chambers suitable for storage and transfer.

Construction of a Fusion Torch System

The fusion torch system would employ the following components: (1) large vacuum systems; (2) various valve systems used for the injection of material into the plasma and for the recovery of the separated species; (3) wall materials able to tolerate large energy flux; and (4) magnetic field coils.

Under the controlled fusion program and due to the development efforts by NASA, large, high throughput vacuum systems have been developed. For example, diffusion pumps handling 50,000 to 150,000 liters per second have been designed. The vacuum in the plasma source region would have to be much higher than that in the interaction region. It is in the preparation of the source plasma that careful attention to vacuum conditions will be necessary. The connection region should be so designed as to prevent contamination of the plasma source region by material in the interaction region. Thus, the interaction, separation and collection regions would be operated at relatively high pressures. The following vacuum levels could be expected in the various regions: 10^{-4} to 10^{-5} mmHg in the source region; 10^{-2} to 10^{-4} mmHg in the interaction region; 1 to 50 mmHg in the separation region; and 50 to 700 mmHg in the collection region, if magnetohydrodynamic separation was used.

The electrical component requirements can vary, depending on the means chosen to produce the source plasma. One advantage to using fusion plasma technology is the ability to produce large plasmas. Devices with plasmas of many feet in diameter are possible. Steady state, i.e., continuously operating, plasmas can be built with high-frequency or microwave generators. Pulsed plasmas of very high temperatures (up to 60,000,000°C) can be produced now using capacitor bank energy storage. Inductive energy storage systems are under development.

The wall material will also be a function of the selected fusion torch separation process and of the plasma source used. For example, if the vacuum levels noted earlier are typical of an operating system, then in the source region materials must be suitable for high-vacuum operation. Materials in the connection region would need high-thermal conductivity to allow removal of the dissipated heat. (This is because the connection region will be designed with a series of baffles or other structures to condense backscattering elements or compounds from the interaction region.) Copper or aluminum would be likely choices for this region. The materials comprising the walls of the interaction region will need to be resistant to sputtering, be able to withstand high-operating temperatures and have high-structural strength. Due to the use of magnetic fields, the plasma-solid interaction can take place without thermal or physical contact with the container walls, thus alleviating the need for a high degree of corrosion resistance. Stainless steel or titanium would be likely choices for materials of construction for this region. The separation regions would probably be made out of the same material as the interaction region. The collection chambers will present the most difficult materials requirements. If collection of metals in liquid form is attempted this will require very temperature resistant wall materials such as molybdenum or tungsten alloys.

Interlocking valve systems, especially in the material feed and collection regions, would need to be developed. Again, extensive NASA technology is expected to be helpful in this regard.

Large volume, superconducting, high-field magnets have been developed and the capital and operating costs are much lower than those of conventional copper magnets. This technological innovation is one of the main reasons for the surge in interest for the development of economical fusion reactors. In fact, the use of superconducting magnets in place of copper magnets could influence the economics of electromagnetic isotope separation itself.

Energy Requirements

The energy requirements for processing materials are a function of the degree of ionization, vaporization or dissociation required in the process under study. Energy requirements may be calculated using Equation 3.21(1).

$$E = \sum_{i=1}^{N} 23{,}800 \, \frac{\overline{\epsilon}_i \eta_i}{Ai} \qquad 3.21(1)$$

where $\overline{\epsilon}_i$ = the average energy usage in all relevant processing interactions in ev

η_i = the percentage of the total composition represented by species i

Ai = the atomic weight of species i

N = the number of species in the material

E = the total energy requirement in KWH/ton

This equation has been used to calculate the energy required to raise a ton of Al_2O_3 or a ton of typical solid refuse of the states described in Figure 3.21d. While large amounts of energy are required for processing in the complete ionization state, intermediate states with only partial ionization would use much less energy. The values in Figure 3.21d represent the energy which must be absorbed by the solid material being processed. The overall energy requirement will be determined by the efficiency of plasma production from electricity in the source, the efficiency of energy transfer from the plasma to the solid and the efficiency of energy recovery from the process regions. Using advanced plasma generation techniques, ultra-high temperature plasmas can be produced at 80% to 95% efficiency from the bus bar. There are no reliable data on the efficiency of vaporizing the solid; however, it is expected to be high because of the effective thermal transfer from the plasma to the solid. Finally, the wall temperatures in the interaction, separation and collection regions can be high, thus permitting energy recovery and regeneration of electricity at 30% to 40% efficiency.

The degree of purity desired in the end products will be an important factor in determining the overall system energy and cost requirements. The separation by the fusion torch of copper from iron in a waste automobile would require relatively unsophisticated techniques while the separation of isotope is very expensive.

Special Considerations

The preceding remarks were based on the use of electricity to produce source plasmas and the discussion has been general since little experimental data is available.

One purpose of proposing the "fusion torch concept" was to stimulate interest in the use of the science and technology that have been developed under the fusion power program to meet both near-term specialized recycling tasks and long-term total recycle capabilities. The near-term efforts can be investigated using source torches which obtain their energy input from electrical power sources and reactor torches which would use plasma generated by a fusion reactor.

The use of a reactor torch would have the advantage of eliminating the need to first produce electricity before producing a plasma. Assuming a 33% efficiency for generating electricity, this would cut the overall energy requirements by a factor of 3. (Note that this does not change the numbers in Figure 3.21d.) A fusion reactor will not be available for some time in the future (estimates range between 20 and 30 years) and the design of the first reactors will be devoted to electrical power generation. The fusion reactions either require or lead to tritium production and careful handling of tritium will be necessary to avoid health hazards in the recycled materials.

Status

The "fusion torch concept" has been extended and expanded due to the talents and efforts of many individuals.

The Boeing Research Laboratory in Seattle, Washington, is devoting a sizable company effort to the development of a source torch for the reduction and separation of aluminum ore and other applications. At the Johns Hopkins Applied Physics Laboratory in Baltimore, Maryland, plasma-solid interactions are being studied as applied to aluminum ore reduction. At Texas Tech University, the plasma-solid interactions are being studied. The Arizona State University has built a source torch and, using a quick-quench separation technique, has produced, from fluorspar and carbon black, CF_4 (useful for Teflon production) and CaC_2 (useful for acelylene production).

At the University of Wisconsin, an extensive study of the feasibility of fusion torches is being completed.

REFERENCES

1. Eastlund, B. J., and W. C. Gough: *Bull. of Am. Phys. Soc.*, vol. 11, no. 13, p. 1564, November 1968.
2. ———: "The Fusion Torch—Closing the Cycle from Use to Reuse," WASH-1132, May 15, 1969.
3. ———: "The Fusion Torch—Unique Applications of Ultra-high Temperature Plasmas," Proceedings of the Conference on Nuclear Fusion Reactors, Culham, England, September 17–19, 1969.
4. ———: "The Fusion Torch—A New Approach to Pollution and Energy Usage," AICE Chemical Engineering Progress Symposium Series, vol. 66, no. 104, 1970.
5. Gough, W. C.: "Why Fusion?", WASH-1165, June 1970.
6. Eastlund, B. J.: Pollution Control Is Elementary—with Fusion Plasmas, *Water and Pollution Control*, January 1971.
7. Gough, W. C., and B. J. Eastlund: The Prospects of Fusion Power, *Scientific American*, February 1971.
8. ———: "Energy, Wastes and the Fusion Torch," paper presented at the AMA 8th Congress on Environmental Health, N.Y.C., April 26–27, 1971.
9. Gough, W. C.: "Possibility of Fusion Reactors as Radioactive Waste Burners," a compilation of material for the CTR Technology Group, July 13, 1971.
10. Savage, H. W., ed.: "Separation of Isotopes in Calutron Units," National Nuclear Energy Series, Division I, vol. 7, 1951.
11. Wakerling, R. K., and A. Guthrie: "Electromagnetic Separation of Isotopes in Commercial Quantities," National Nuclear Energy Series, Division I, vol. 4, 1951.
12. Hendricks, C. D.: University of Illinois, private communication.
13. Bonnevier, B.: Diffusion Due to Ion-Ion Collisions In A Multicomponent Plasma, *Arkiv for Fysik*, vol. 3, p. 255, 1966.
14. Crawford, J. D.; B. W. James; and C. N. Watson-Munro: International Conference on Phenomena in Ionized Gases, Bucharest, Rumania, p. 61, August 31-September 6, 1969.
15. Bonnevier, B: "Experimental Evidence of Element and Isotope Separation in a Rotating Plasma," Division of Plasma Physics, Royal Institute of Technology, Stockholm; Sweden, Report no. 70-08, June 11, 1970. (To be published in *Plasma Physics*.)
16. Lehnert, B.: "Rotating Plasmas," Division of Plasma Physics, Royal Institute of Technology, Stockholm, Sweden, Report no. 70-37, November 1970.
17. Morozov, A. I.: "Stationary Plasma Accelerators and Their Applications in Thermonuclear Research," Conference on Plasma Physics and Controlled Nuclear Fusion Research, International Atomic Energy Agency, August 1968.
18. Tuckfield, P. G., and F. R. Scott: *Plasma Physics Journal of Nuclear Energy*, part C 8, p. 271, 1967.
19. Porter, W. A.; M. O. Hagler; and M. Kristiansen: *IEEE Transactions on Nuclear Science*, February 1971.

6.1 ENVIRONMENTAL INTERRELATIONSHIPS

Man's environment is a web—a complex network of totally interactive beings, forces and events—wherein stress on one of the strands affects the entire web.[1] A panoramic view of these interrelationships is presented here to give the environmental engineer a greater perspective for his work. The story of man as he molds and is molded by the environment is traced from Neanderthal to contemporary man. Possibilities for the society of the future and the steps that must be taken to ensure a successful transition into that future are also discussed.

The Historical Relationship of Man to His Environment

Our earth is about 4½ billion years old. Fortunately, the sun provides an abundant energy source to power and create change in the environment. A brief history of these changes is traced in Figure 6.1a. Within a few billion years, the earliest forms of life had appeared. As time went on, more advanced forms of life developed with the environmental forces acting as selective agents. An example of the power of these forces is the extinction of the dinosaurs from the earth some hundred million years ago. These creatures had become too specialized and had only a narrow range of ecological adaptation. When a slight shift of the ambient temperature altered the earth's vegetative cover, certain edible plants were removed from the diet of the herbivorous which in turn were removed from the diet of the great carnivores and brought about their extinction.

Only in the last few million years have human-like creatures existed on earth. Originally probably several gender and species of erect, man-like primates existed. However, only one gender, *Homo*, and of this one, only one species *sapiens*, has survived.

The effect that the environment of this earth has already had upon shaping *Homo sapiens* or man is not often recognized. Although the size and shape of humans can be shifted in a few generations due to factors such as nutrition, there exist differences which may be viewed as genetic adaptations to particular environmental extremes. For example, animals, including man, living in colder regions are larger than members of the same species inhabiting warmer regions; this is known as Bergmann's rule. Warm-blooded animals need to maintain a constant internal temperature and, therefore, in cold temperature

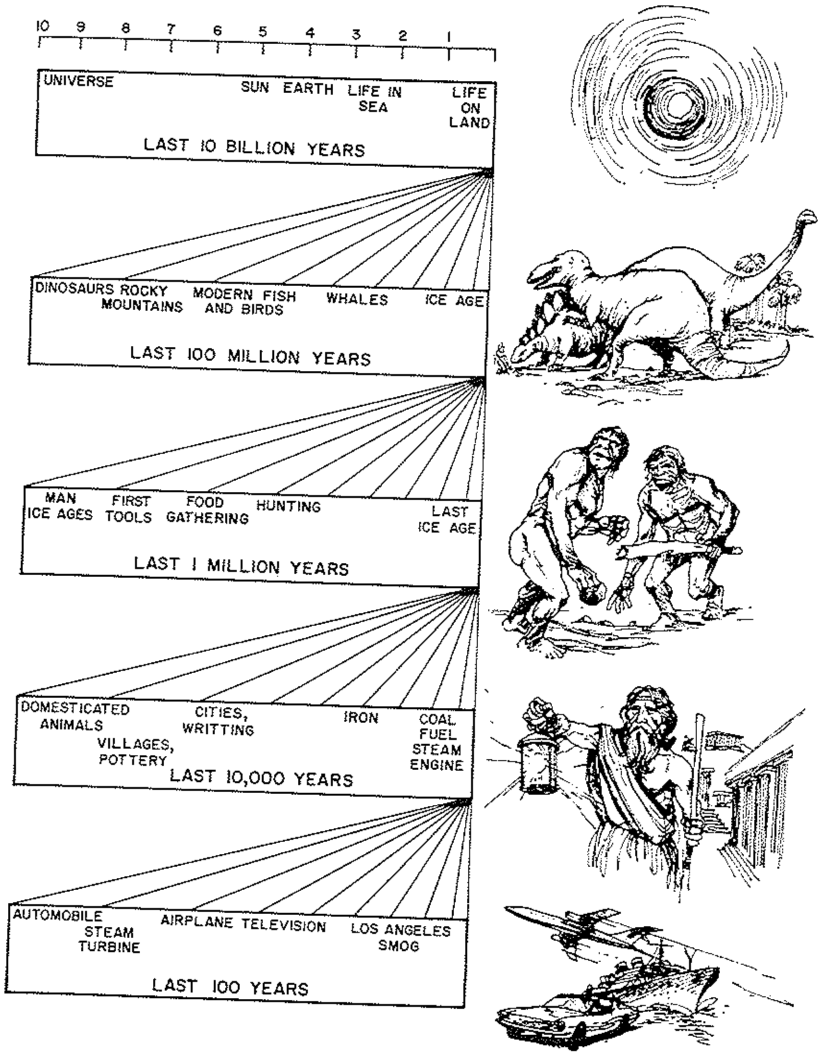


Figure 6.1a An historical perspective of man and energy. *(Taken from an original AEC drawing)*

regions, the larger bodied creature (all else being equal) is more efficient than the smaller because it has less surface area in proportion to its volume. At the same time, the body shape should be such as to conserve heat for cold weather living. Thus, the surface area of the skin should be minimized in relation to the volume of the body, giving a stocky body with the limbs close to the warm, central core. Both are characteristics of arctic people. To adapt to the high (and relatively dry) temperature of the desert, the human should tend toward linearity. There is a distinct tendency for the more linear groupings to be associated with this environment. A more specialized case is the large rumps of Bushmen and Hottentots. The fat rumps provide a storage location for chemical energy for use during periods of food-scarcity. Since the energy storage is in a restricted location, it provides minimum interference with the body's heat dissipation to the environment.[2,3]

Another example is skin pigmentation. Until modern science developed substitutes, mankind resembled the living plant in that he was dependent upon the direct use of solar energy for his health. Vitamin D is essential for the proper use of calcium in the body. It is not present in significant amounts in the normal diet and, therefore, is synthesized in the body by the skin in a photochemical reaction using the ultraviolet energy from the sun. The amount of vitamin D in the body must be maintained within a limited range. Too little results in the bowlegs and twisted spines associated with rickets; too much results in hypervitaminosis D with the appearance of kidney stones, since the human body is unable to selectively destroy toxic doses of vitamin D once they have been absorbed. For man, the rate of vitamin D generation is regulated by the pigmentation and keratinization of the skin; i.e., the darker the skin, the more ultraviolet is reflected and the less vitamin D is synthesized.

Since the ultraviolet energy available on earth varies depending upon latitude, there exists a direct correlation for man between skin pigmentation and latitude. For example, by 100,000 years ago, man in Europe had adapted to dim ultraviolet light in the northern latitudes through almost a million years of evolution. This area of the world was occupied by one subspecies of *Homo sapiens* commonly referred to as the Neanderthal man. He was white, hairless and intelligent. It was his fate to face up to the last ice age. However, unlike the dinosaurs, the Neanderthal man had shown great flexibility in adapting to environmental changes. He had harnessed supplemental energy through the use of fire and had developed tools and weapons to gain control over nature.

The technological solution to the glacial cold, developed by these early environmental engineers, was to dress their infants warmly in animal skins during the winter months. However, the artificial body cover used in defense against the harsh, damp cold of the ice age in Europe shut off the ultraviolet irradiation of body chemicals necessary to produce the vitamin D. By drastically reducing the area of skin exposed to solar ultraviolet energy, rickets became of epidemic proportions. This was disastrous for the Neanderthals; infants crippled by rickets had a low probability of survival because they could not hunt game effectively. Thus, only some 35,000 years ago, a subspecies of present day man died out in western Europe when a successful short-run solution to an environmental change eventually proved disastrous.[4,5]

While the environment was making its impact upon man, the long history of man's impact upon the environment began. The first big ecological change that may reasonably be attributed to man was the extinction of large mammals roughly 30 or 40 thousand years ago. In North America, 70% of the large mammals became extinct along with their predators and scavengers. Since there were no indications that mass extinction of small animals, plants or marine forms took place, the cause appears to be man's hunting rather than the great climatic changes of the period.

As man continued this transition from precivilized to civilized society, our early hunting ancestors proceeded to invent agriculture which resulted in an even greater impact upon the environment. Overgrazing and lumbering were at least partly responsible for the *desertification* of much of northern Africa and for the expansion of the great Thar Desert of north western India. Heavy logging and the clearing of land for agriculture denuded many of China's watersheds, leading to destructive flooding on her rivers. In North America, large areas of what previously was first-rate grazing land was turned into desolate expanses of sandy desert by Navaho sheepherding.[6]

As we move from the recent past into the present there is another danger appearing. The objective of modern agriculture is to grow pure strands of crops, single species of plants that can be eaten directly by man; or single crops that provide food for animals that can be eaten. The shorter the food chain, the more efficient the conversion of solar energy into human food. Thus, forests and grasslands communities, containing many different kinds of plants, insects and animals, are displaced by fields of single crops from which man attempts to exclude other plants, insects and animals. This trend toward simplification is dangerous. A general principle emerging from ecological studies is that the more complex the ecosystem, the greater its stability. Thus, man is now moving towards a more arbitrary, more artificial, more precarious relation with the ecosystem of this earth. Thus, *Homo sapiens* are becoming more like the dinosaurs—dependent upon a highly specialized ecosystem.

The Present Relationship of Man to His Environment

Since early history, the earth was essentially a closed system in which materials were recycled and reused. The primary links in nature's closed materials systems are: (1) the energy source—sunlight; (2) the earth's nonliving resources—oxygen, water, etc.; (3) the plants from plankton to trees that produce carbohydrates via photosynthesis; (4) the consumers which feed on the plant products or on other consumers; and (5) the decomposers—bacteria, fungi and insects that close the cycle by breaking down the dead producers and consumers and return the chemical compounds to the earth's pool of resources.

For the million or so years man has been on earth, he has both been changed by and has made changes in the earth's environment. Until very recently, however, these changes have represented only a small perturbation in a large system and have not threatened the self-healing balance of nature's closed system. At the root of our growing environmental crisis is the fact that man is now capable of making large enough perturbations in the total earth's system to upset the present balance of nature.

One reason why man is capable of creating such large perturbations is his control of energy. Man is the only animal on earth able to harness energy other than that obtained through the conversion of food and air inside its body. This event occurred 300,000 to 400,000 years when man first used fire. Until about 800 years ago, the sole source of man's auxiliary energy was his daily sunlight, i.e., solar energy. This was stored in wood which was burned for heat or in the food eaten by the beasts of burden which assisted man in his work. Then man discovered coal, a reserve of concentrated energy created over the last half billion years or so when a small trickle of the sun's energy had been trapped and stored in the form of fossil fuels. The successful harnessing of sizeable amounts of this concentrated energy only a few hundred years ago—first as inputs to agriculture and then to industrial products—is the real source of man's wealth and also of his present day problems.

To illustrate the role of energy in determining the economic well-being of a society refer to Figure 6.1b. In terms of *total* energy, the main source for any society remains the sun, which through the cycle of photosynthesis produces the food that is the basic fuel for sustaining the population of that society. The efficiency with which the sun's energy can be put to use, however, is determined by a feedback loop in which auxiliary energy sources form a critical link. The auxiliary energy (derived mainly from fossil fuels) "opens the gate" to the efficient use of the sun's energy by helping to produce fertilizers, pesticides, improved seeds, farm machinery and so on. The result is that the food yield (in terms of energy content) produced per unit area of land in a year goes up by orders of magnitude. This auxiliary energy input, when it is transformed into food energy, enables large populations to live in cities and develop industries and new ways to multiply the efficiency of the feedback loop.[7]

During the last few hundred years, mankind used the fossil fuels to obtain large multiplications in this energy feedback loop, but this has not occurred evenly among the peoples of the earth. Today we have a large gap, which is still widening, between the rich and poor nations of the world. The cause of this unequal distribution can be debated. However, Figure 6.1c shows that for large segments of the world, initial fossil fuel energy reserves correlate well with present wealth (GNP), whereas the present population has an inverse relationship with large numbers of people in those portions of the earth which are most lacking in energy and material wealth.

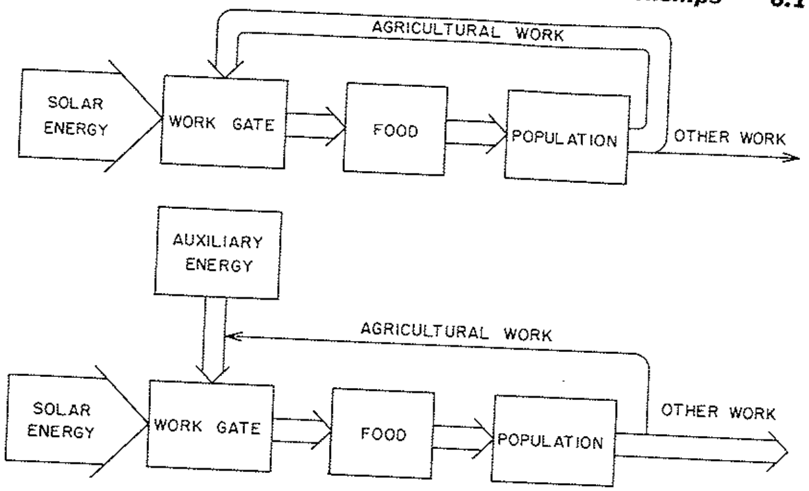


Figure 6.1b Role of auxiliary energy in determining the economic well-being of a society is illustrated by these agricultural feedback loops. In an economically less developed country (top), the bulk of the population must be devoted to the agricultural transformation of the sun's energy into food in order to support itself at a subsistence level. In an economically more developed industrial country (bottom), auxiliary energy sources "open the gate" to the more efficient utilization of the sun's energy, making it possible for the entire population to maintain a higher standard of living and freeing many people to live in cities and develop new ways to multiply the efficiency of the feedback loop. (*From "The Prospects of Fusion Power" by W. C. Gough and B. J. Eastlund, Scientific American, 1971*)

The nations of North America and Europe (including all of the USSR) have 82% of the fossil fuel energy reserves of the world.[8] These same nations now have 79% of the world's wealth in terms of GNP, yet they represent only 27% of the world's population.[9]

This gap between the rich and the poor of the world is still widening. The feedback process shown in Figure 6.1b is one cause of this because many of the poorer nations lack the where-with-all to get the amplification process of the feedback loop underway. A secondary effect is the rapid transfer of limited technologies from wealthy nations already well into the feedback process to poorer nations who have not yet begun the process. Advanced medical technology and food assistance programs, when provided to the underdeveloped countries without properly considering the nature of the overall feedback process, cause runaway population growth and a further widening of the gap between the developed and underdeveloped nations of the world. Thus, one requirement to reduce the danger of world instability

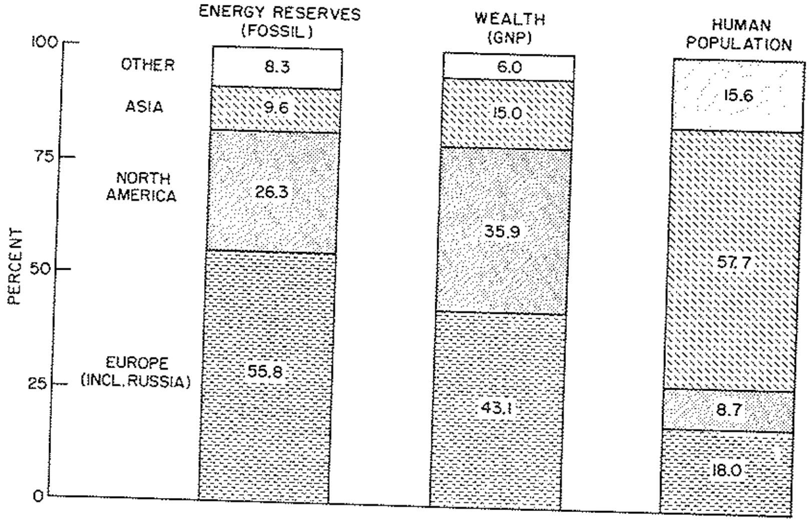


Figure 6.1c Distribution of world energy reserves, wealth and population. *(Taken from an original AEC drawing)*

in the future will be an abundant and hopefully inexpensive energy source whose fuel is available to all nations. However, there may not be sufficient time available to await the routine development of new energy technologies to help the feedback process get underway.

A more detailed look at what energy means to society appears in Figure 6.1d. On the upper left is a plot of energy consumption versus gross national product on a per capita basis for the nations of the world. Although imperfect, the GNP is a good measure of material living standards. The very close relationship between energy use and living standards is apparent. The United States stands alone; with 6% of the world's population, it consumes about one-third of the total auxiliary energy used on earth.

The use of materials versus energy consumption is shown in the upper right on Figure 6.1d, which is the same kind of plot as for standards of living and energy. The data are for steel which is a good indicator of overall materials' use. Again, the United States with 6% of the world's population consumes over one-third of the earth's minerals. This nation is becoming increasingly dependent upon the less developed nations for the supply of these materials. Three quarters of a ton of each large United States automobile comes from foreign sources.

Almost everything people consume is eventually turned into wastes since there is relatively little recycling. The fact is that no material is really "consumed"; its form is altered into one which is less desirable for human use. Thus, the lower part of Figure 6.1d projects that pollution will follow the

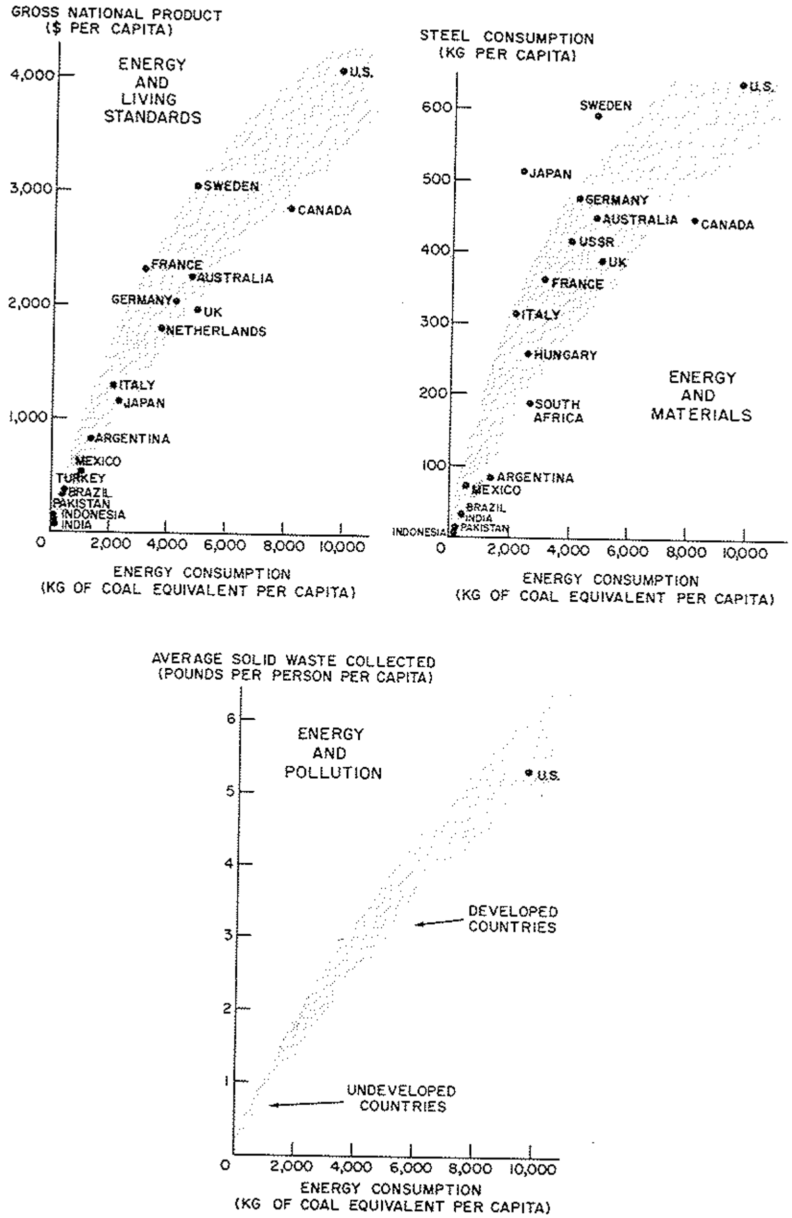


Figure 6.1d Relationship of energy to living standards, materials use and pollution. *(Taken from AEC drawings from "Why Fusion?" by W. C. Gough, June 1970)*

same pattern as living standards and materials use.[10] As the use of energy is increased, so is the standard of living, the use of materials and the amount of wastes that are generated. This is why the United States has a major pollution problem. Without recycling, there are only three sinks for these wastes—the oceans, the atmosphere and the land. The rivers transport much of the wastes to the ocean in the form of water pollution. When wastes are burned, they create particulate matter and gases that pollute the air. If the wastes are buried, groundwater and soil pollution can result. Most pollution programs that environmental engineers will carry out attempt to put wastes into less objectionable forms and locations.

The per capita data on wealth, materials' use and pollution must be multiplied by population figures to obtain total worldwide values. The world population is now on a very steeply rising curve as shown in Figure 6.1e. The curve is rising faster than one would expect using a simple exponential extrapolation. That is, *the rate of growth* of the world population has been increasing, thus continually decreasing the time required for the world population to double. In 1650, the growth rate was 0.3%; if this remained constant, each doubling of the population would take 250 years. At the present time, the growth rate is 2.1%, with each doubling taking only 32 years. The rate of population growth is the birth rate minus the death rate with both expressed as a percentage of the total population per year. Thus, Figure 6.1e is really a conservative projection into the future, since it assumes that the growth rate will remain constant. A positive force acting to slow down the population explosion is the decrease in birth rate with the wealth (GNP) per capita as shown in the upper part of Figure 6.1f. Yet, at the same time, increased wealth

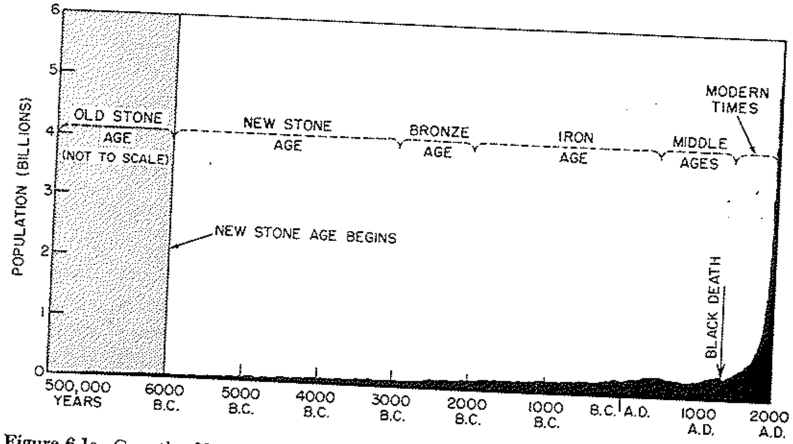


Figure 6.1e Growth of human population. *(Taken from redrawing by AEC of figure from Population Bulletin, Population Reference Bureau, Inc., vol. XVIII, no. 1, February 1962)*

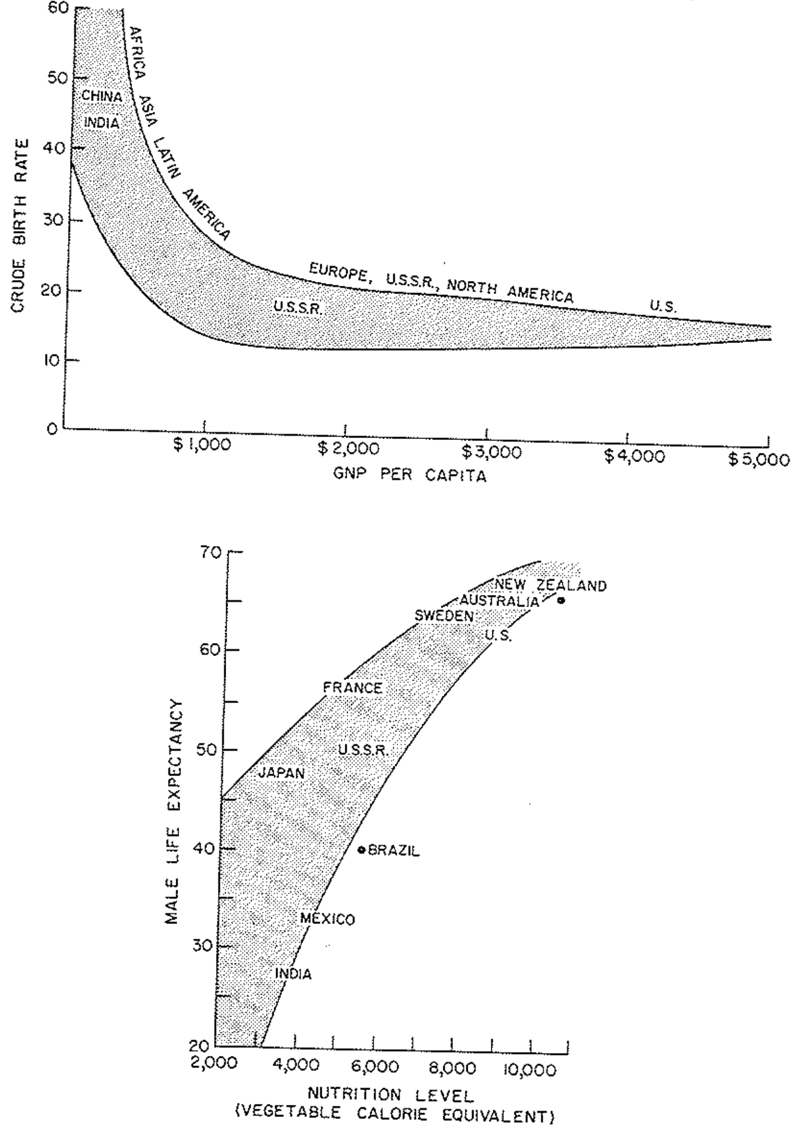


Figure 6.1f Factors affecting population growth. *(U.S. Agency for International Development, Office of Population, "Population Program Assistance," GPO, Washington, D.C., 1970; and "Population and Food" by Michel Cepede, Francois Houtart, Linus Grond, Sheed and Ward, Inc., 1964)*

results in improved nutrition level which as shown in the lower part of Figure 6.1f increases life expectancy and, other factors being constant, would result in a decreased death rate.

The finite earth has a limited amount of suitable land for agriculture. This has been calculated to be 7.86 billion acres (3.2 billion hectares). About half of this is under cultivation today and the rest will require high capital expenditures before it will produce food. Yet at the present time, over half of the population of the less developed countries of the world are inadequately nourished. In addition, although agricultural production is increasing in these countries, the production per capita is barely holding constant at its present inadequate level.

The optimistic assumption that the financial resources will be obtained to use all the arable land available is made as the basis for Figure 6.1g. Here the amount of land needed to feed the growing world population is assumed to be the present world average of 0.4 hectares per person (less than half that required for present United States standards). The world population is assumed to grow at the projected rate of 2.1% per year; as a result, the amount of land available will decrease in the future due to the land required for housing, roads and power transmission.

Figure 6.1g illustrates that, with an exponential population growth within a limited space, the world can move within a relatively few years from a situation of great abundance to one of great scarcity. The use of less land for living space or the doubling and even quadrupling of land productivity postpones the crisis only a few decades at the most.[11]

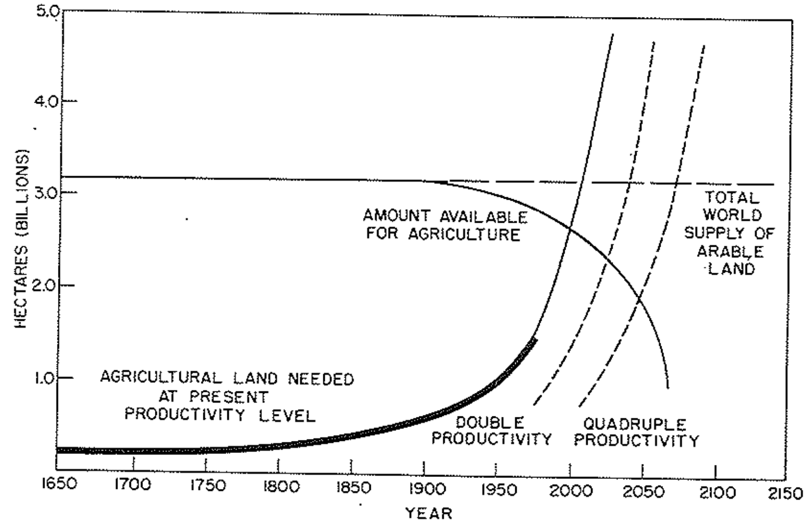


Figure 6.1g Relationship between food supply, land area and population. *(Taken from "The Limits to Growth" by D. H. Meadows, et al., Universe Books, N.Y., 1972)*

The ability to operate an industrial society and to feed large numbers of people depends upon the natural resources available. Like land, there exists only a fixed amount of resources on earth. With an exponential population growth and living standards rise, there has been a corresponding sharp rise in the world's demand for iron, copper and other minerals. The richest mineral deposits and districts in the world are being depleted first. Deposits that were created over billions of years are being depleted in decades. Thus, the grade of ore being mined has been decreasing, which, in turn, has required an increased use of energy.

One result has been that the developed nations are becoming increasingly dependent upon the less developed nations for the supply of raw materials. Table 6.1h lists both the staples of an industrial society such as iron and aluminum plus the "vitamins" of an industrial society such as molybdenum, nickel, tin, etc., needed for the stainless steels, galvanized steel and other specialized items. These metals occur in the earth's crust in a concentration

Table 6.1h

DEPLETION OF WORLD RESERVES OF COMMERCIAL GRADE ORES[a]

Resources	*Abundance In Earth's Crust (ppm)*	*Supply at Current Rate of Usage (yr)*	*Projected Rate of Growth in Usage (%/yr)*	*Supply Assuming Projected Growth Rate in Usage (yr)*
Aluminum	81,300	100[b]	6.4	31[b]
Iron	50,000	240	1.8	93
Zinc	220	23	2.9	18
Chromium	200	420	2.6	95
Nickel	80	150	3.4	53
Copper	70	36	4.6	21
Tungsten	69	40	2.5	28
Tin	40	17	1.1	15
Lead	16	26	2.0	21
Molybdenum	15	79	4.5	34
Mercury	0.5	13	2.6	11
Silver	0.1	16	2.7	13

[a] Uses data from *The Limits To Growth*, Meadows, et. al., Universe Books, New York, New York, 1972 and from the *Handbook of Chemistry and Physics*, R. C. Weast, Ed., The Chemical Rubber Company, 50th Edition, 1969–1970.

[b] Bauxite

of a very few parts per million and will be difficult to obtain once the high grade ore is gone. Two values have been given in Table 6.1h for the number of years for which the present known reserves of a resource will last. The first assumes that the current rate of usage will continue indefinitely. The second takes into account that the rate of usage has been growing exponentially; in many cases, it is growing even faster than the population. The effect of exponential growth is to reduce the probable period of availability of iron from 240 to 93 years and of aluminum (bauxite) from 100 to 31 years.

Detailed computer models have been used to study the interrelationships in the materials problems. The conclusions were very clear:

> Given present resource consumption rates and the projected increase in these rates, the great majority of the currently important nonrenewable resources will be extremely costly 100 years from now. The above statement remains true regardless of the most optimistic assumptions about undiscovered reserves, technological advances, substitution or recycling, as long as the demand for resources continues to grow exponentially.

The effect of the present trends in population growth, food demands, industrialization and energy use are already being translated into exponential curves for various kinds of pollution. However, no upper bounds can, as yet, be indicated for the exponential growth curves of pollutants because the upper limit of mans ability to perturb the natural ecological balance of the earth is not known. How much CO_2, atmospheric dust or thermal pollution can be released without causing irreversible changes in the earth's climate can only be speculated. No one knows how much radioactivity, lead, mercury or pesticide can be absorbed by plants, fish or human beings before they begin to die in large numbers. In addition, there is typically a long delay between the release of a pollutant into the environment and the appearance of its negative effects on the ecosystem. Another effect of this lag time is that even after decreasing the input of a long-lived pollutant into the environment, its absorption into the tissues of living organisms can still continue to rise for decades. The environmental engineer obviously needs some data on the effects of pollutants and in the meantime must exercise conservatism.

The Future Relationship of Man to His Environment

It is clear that over the next few decades—before the end of this century—the human race will have to face and resolve challenges that may well determine the shape of its life for centuries to come, if not its very survival. To help define these challenges, there has been a rapid growth in recent years of research into the future. The aim of this research is to develop rational forecasts of future possibilities open to society.

In the United States, the future research field has approximately 600 full-time workers plus about 500 part-time workers. At present, future research has had very little impact on national policy. The field is not well organized or supported. The work is very uneven in quantity, range and quality of research. Much is narrow and specialized work in support of relatively short range planning. However, the potential contribution of futures research to society is very great. It deserves close scrutiny by those engaged in environmental planning and engineering.[12]

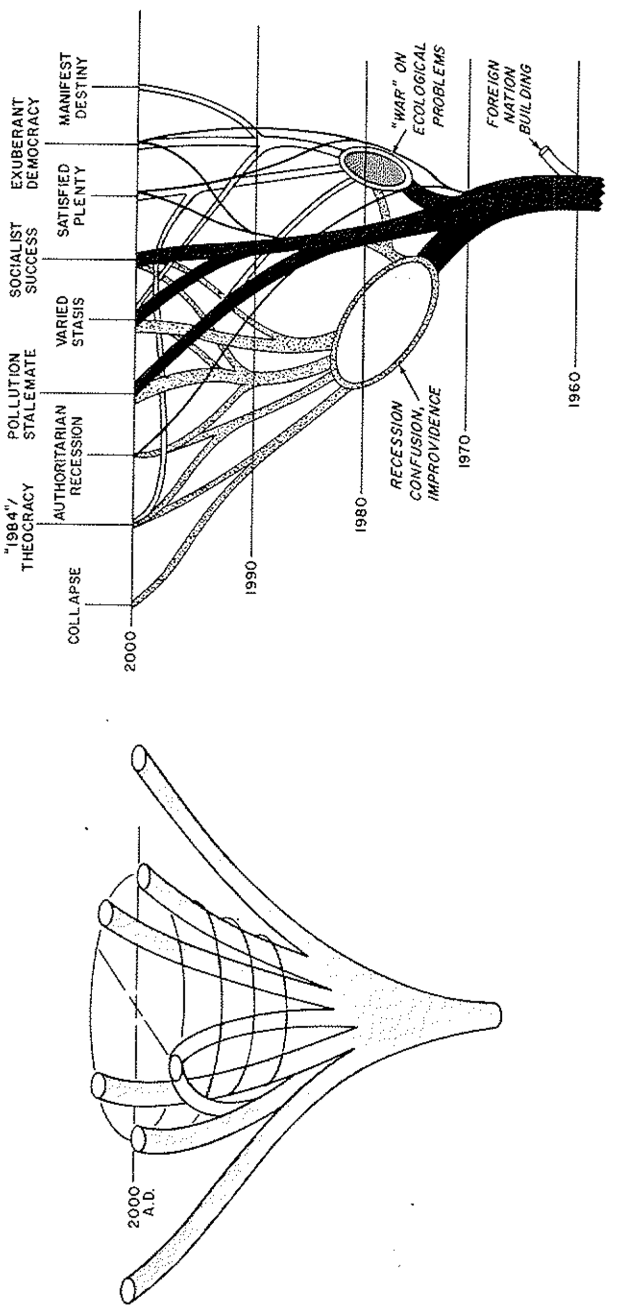
One example of futures research is the work being carried out at the Stanford Research Institute in Menlo Park, California. The approach taken is characterized by maximum scope. A newly developed technique is being applied whose underlying philosophy is similar to the relaxation methods of mathematical physics that have been used to model complex dynamic systems (as in thermodynamics). The procedures constitute a method for qualitative analysis of complex fields of partly or wholly nonquantifiable information. The result is the construction of alternative future histories. The ultimate power of the method lies in the possibility of continued refinement, through systematic iterations, of a whole set of feasible futures seen as a whole.[13]

Serious efforts have been made to search out distinctive lines of evolution that are characterized at each date in the future by internal consistency among their parts and by sequential continuity from the past through the present and from date to date in the future. The result has been that the alternative futures are to be numbered only in dozens, instead of the thousands that might be expected. For practicality reasons, a limited set, fewer than ten, must be selected for further evaluation. When such a set is developed, it forms the kind of "tree" shown in the upper portion of Figure 6.1i of the projections of alternative futures is represented by a tube taking its own individual route away from the present.

Although results to date must be considered tentative and preliminary, a tree for alternative futures for the United States is shown in Figure 6.1i. The "branch points" in this tree are of particular significance since they identify crucial choices between alternative futures. A representation of the two dimensional surface obtained by making a slice through the year 2000 is shown in the lower portion of Figure 6.1i.

The two dimensions result from the fact that the various "year 2000" alternative states tend to differ in two especially significant dimensions. One concerns the degree to which the society is both competent and motivated to attempt control of its own destiny. The other relates to the degree of "openness," which implies flexibility, the social coherence which flows from trust, tolerance for diversity and the ability to sustain decentralized decision-making without undue internal violence.

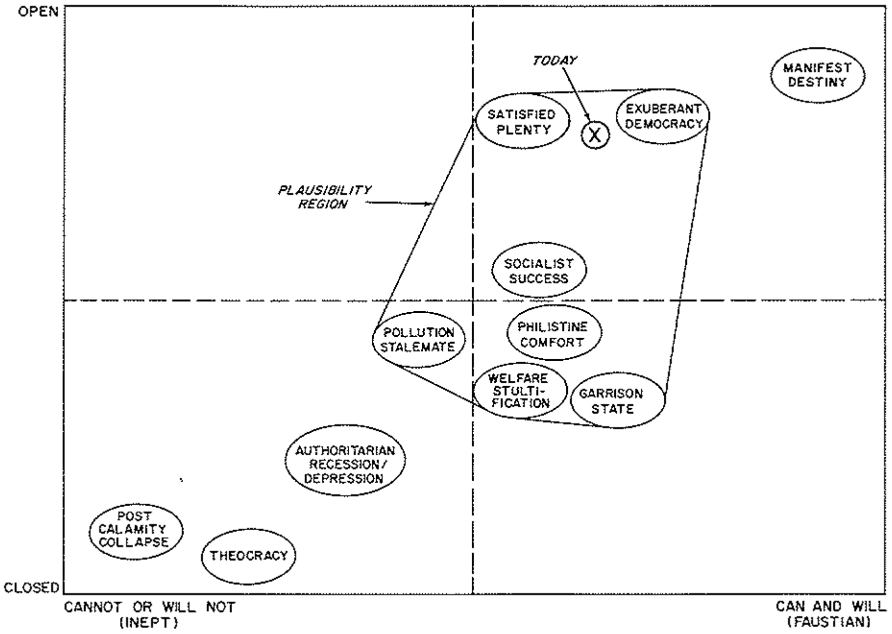
A significant overall conclusion of the work to date is that of the many feasible futures, very few manage to avoid some period of serious trouble between now and 2050. The few that do, appear to require a dramatic shift of values and perceptions with regard to the present world problems. For



CROSS SECTION OF TREE
OF ALTERNATIVE FUTURES FOR U.S.

TYPICAL TREE
OF ALTERNATIVE FUTURES

Figure 6.1i Alternative futures. *(Taken from "Projecting Whole-Body Future Patterns—The Field Anomaly Relaxation (FAR) Method," Stanford Research Institute Memorandum Report EPRC 6747-10, February 1971; and "Alternative Futures and Educational Policy," Stanford Research Institute Memorandum Report EPRC 6747-6, February 1970)*



SLICE THROUGH TREE AT THE YEAR 2000

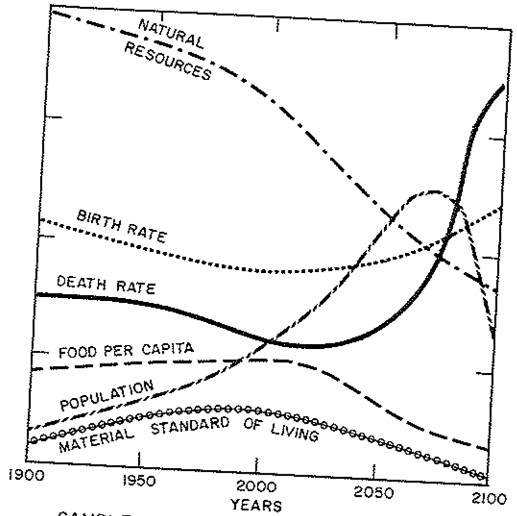
example, to even reach some of the desired alternate futures in the upper right hand corner of the two-dimensional lower view of Figure 6.1i requires an all-out national effort on ecosystem problems of a magnitude approaching that of World War II and with similar unification of national will, launched no later than in the period of 1975 to 1980.[14]

Another fact which has gradually evolved from the future studies at Stanford is that the problems facing the world appear to be surface manifestations of a fundamental cultural condition. The roots of the present problems appear to be implicit in the basic operative premises of our present industrialized culture. These operative values have served to bring the world to its present state of development, but will result in intolerable problems in the future if not changed. Although various aspects of the world macroproblem may be postponed by certain technological achievements, the conclusion is that the paramount and urgent task for the nation and the world will be to change those premises whether they be explicit or implicit. As an example, six of these premises are quoted on page 952:[15]

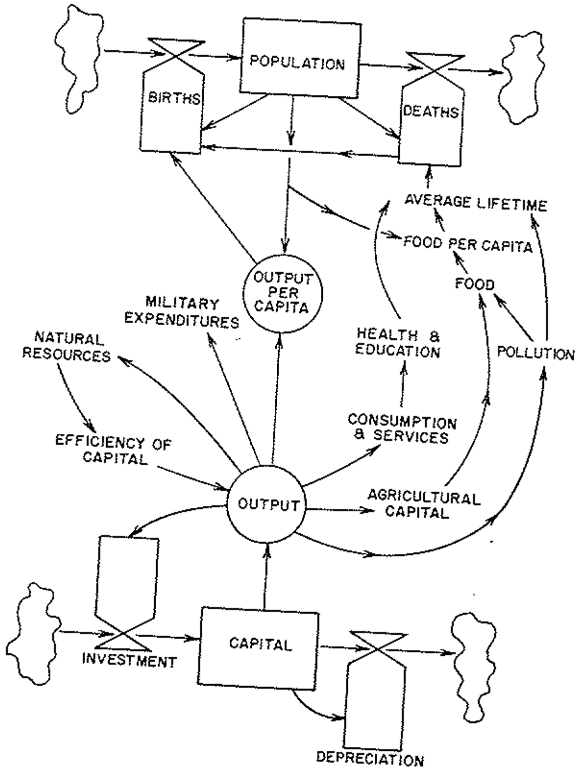
1. The premise that the pride of families, the power of nations and the survival of the human species all are to be furthered (as in the past) by population increase.
2. The "technological imperative" that any technology that *can* be developed and any knowledge that can be applied *should* be.
3. The premise that men are essentially separate, so that little intrinsic responsibility is felt for the effects of present actions on remote individuals or future generations.
4. The premise that man is separate from nature and, hence, that nature is to be exploited and "controlled" rather than cooperated with.
5. The "economic man" image, leading to an economics based on ever-increasing GNP, consumption and expenditure of irreplaceable resources.
6. The premise that the future of the planet can safely be left to autonomous nation-states, operating essentially independently.

Future research at the Massachusetts Institute of Technology projects the present trends in population, industrialization, pollution, food production and natural resources depletion. The basic operative premises of present society were assumed to remain unchanged and a computer simulation using a global model of present trends was applied through the method known as system dynamics and characterized by the presence of the feedback loop. A sample simulation of the global model used by the MIT researchers appears in Figure 6.1j, together with the basic interactions used in the model. A complex flow diagram would be needed to represent the large number of interactions considered in the computer model. The conclusions of the MIT work to date are:[11]

1. 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.
2. 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.



SAMPLE SIMULATION OF GLOBAL MODEL



BASIC INTERACTIONS USED IN MODEL

Figure 6.1j Computer simulation of world trends.' (Courtesy of the World Future Society, Washington, D.C.)