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Nuclear Plants and Nuclear Niches: On the Generation of Nuclear Energy During the Last Twenty Years

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Abstract — *The penetration of nuclear energy around the world is analyzed by logistic analysis. The results show that despite some ups and downs, nuclear use keeps up a regular rate of growth, and, worldwide, grows much faster than could be expected from previous regularities in the penetration of oil and gas. This growth may be attributed to the fact that nuclear energy found in the electrical grid a ready-made distribution network. The question of what network to develop next is crucial if the pace is to be kept.*

Stations nucléaires et niches nucléaires: Sur la génération d'énergie nucléaire pendant les derniers vingt années

Résumé — *La dispersion de l'énergie nucléaire dans le monde est analysée par le biais d'equations logistiques. Les résultats montrent que malgré des hauts et bas, l'utilisation de l'énergie nucléaire se maintient à une augmentation regulière et, au niveau mondial, elle est répandue beaucoup plus rapidement que l'on pourrait attendre de la dispersion antérieure continue du pétrole et du gaz méthane. Cette augmentation peut être attribuée au fait que l'énergie nucléaire a trouvé dans le réseau électrique un système de distribution déjà complet. La question c'est quel réseau est important à realiser ensuite, pour la continuation de cette même vitesse de dispersion.*

Nukleare Anlagen und nukleare Nischen: Über die Generation de Kernenergie während der letzten zwanzig Jahre

Zusammenfassung — *Die Verbreitung der Kernenergie in der Welt wird anhand logistischer Analysen untersucht. Die Ergebnisse zeigen, daß, abgesehen von einigen Schwankungen, die Verwendung der Kernenergie eine kontinuierliche Zuwachsrate beibehält und ist, weltweit gesehen, wesentlich schneller als aufgrund früherer Beobachtungen über die Verbreitung von Mineralöl und Erdgas erwartet werden kann. Dieser Zuwachs kann darauf zuruckgeführt werden, daß die Kernenergie im elektrischen Netz ein fertiges Verteilungsnetz vorgefunden hat. Die Frage, welches Netz als nächstes zu entwickeln, ist wesentlich, wenn das Tempo beihalten werden soll.*

Nuclear energy is certainly one of the main threads in the scientific activity of Dr. Alvin Weinberg, who was involved in it since the heroic days of Admiral Rickover. Thirty years later it is fitting to pause and assess where nuclear energy now stands and try to determine what the future holds for it.

The technique I will use to analyze the position of nuclear energy is taken from formal Darwinian biology. It assumes that a new technology arising in the world is the analog of a new species appearing in a given environment. If the species is to be successful, it will grow into what ecologists call a *niche*. The concept of niche is very complex and somehow elastic, but it can be measured quantitatively and operationally. The species will expand to fill the niche through a *logistic* growth of the population of its members. So by counting noses (or tails) at certain intervals one can fit the Volterra-Lotka (or Verhulst) equation and calculate the size of the niche.[a]

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[a] References on Volterra-Lotka equations and logistic fitting are quite numerous and easy to find in the literature.

This simple technique, applied to all sorts of things in a socioeconomic system, has shown an extraordinary capacity to fit actual data with a minimum of mathematical infrastructure. This can be done not only in the case of growth into a niche as described above, but also in the case of multiple competition for niches of known size.[1,2]

The general formula for this ecological look at human affairs is given by the Volterra-Lotka equation, which basically embodies Darwin's principle of competition. About 300 cases pertaining to energy and ~400 in the general socioeconomic area were analyzed using this method.

The consistent success of the analysis should be interpreted in Darwinian logic. A background example is shown in Fig. 1, where the competition of primary energies at the world level is depicted. The deviations of the actual data from the equations are rarely more than a few percent, and they are always elastically reabsorbed. Thus, the "squiggles" that emerged in the last ten years in the coal and gas curves should very soon go into reabsorption, based on the readings for the past 100 years. This implies a future where gas and nuclear will be the energy winners, and all others will be losers. There will be plenty of time to cheer, however, since the time constant of these processes is in the range of one century.

The energy crisis in the 1970s did not change the evolution of the oil share, but coal use stopped decreasing and gas use stopped increasing, due to American legislation and cultural dominance. The time constant of penetration, i.e., the time to go from 1 to 50% of the market, is ~100 years, and the line for the nuclear equation has been traced on the principle of "business as usual." The line of the actual share may well bend to that slope in the 1990s when much of the electrical "niche" will be penetrated. Going to saturation at levels similar to coal and gas will presumably require a second energy vector. The nuclear input in Fig. 1 is calculated in terms of nuclear *heat* going into the production of electricity.

The results of the study are best described by the charts and related legends shown in Figs. 2 through 13. These figures trace the penetration of nuclear energy, in terms of the number of reactors connected to the grid and their installed power, from its origins to the present for the world and for major energy-producing countries. They also predict the size of the niche, i.e., the final size of the nuclear industry in the world and in various countries. The fitting equation (see the Appendix) is a three-parameter logistic; since the size of the niche is calculated by best fit, the calculation of the saturation point or asymptote is usually not very precise. The results, however, appear reasonable, and, more important, consistent within themselves.

We can certainly say that for the past 20 years, albeit with the inevitable ups and downs, the logistic frame has fit quite well. With some prudence, the

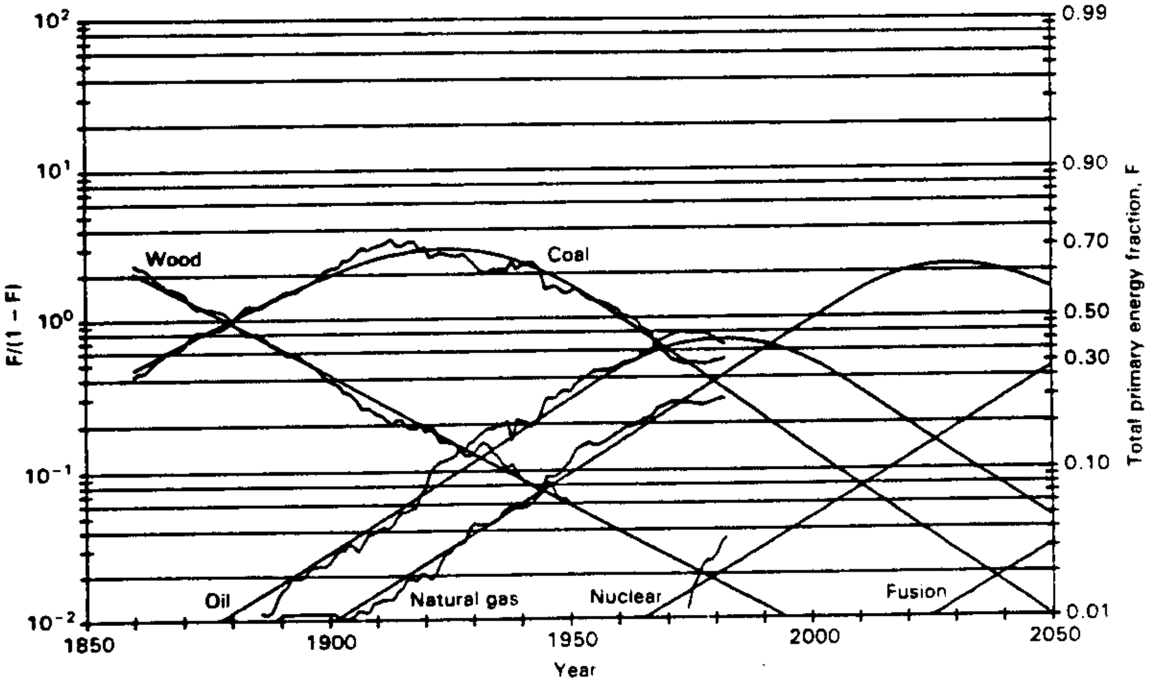

Fig. 1. Historical trends in energy substitution. The amount of primary energy (in coal-tons equivalent) from each primary source is plotted as fraction F of the total energy market with the ordinates expressing $\log F/(1 - F)$. This makes logistics appear as straight lines; the fitting set of the equation is given by the smooth curve.[4]

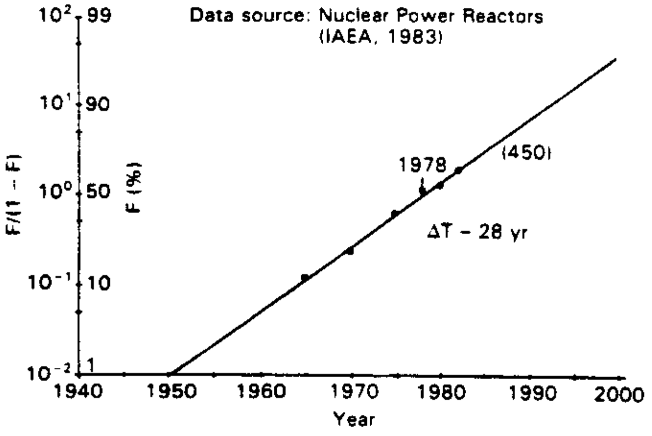

Fig. 2. Number of nuclear power plants worldwide connected to the grid. For an explanation of symbols, see the Appendix.

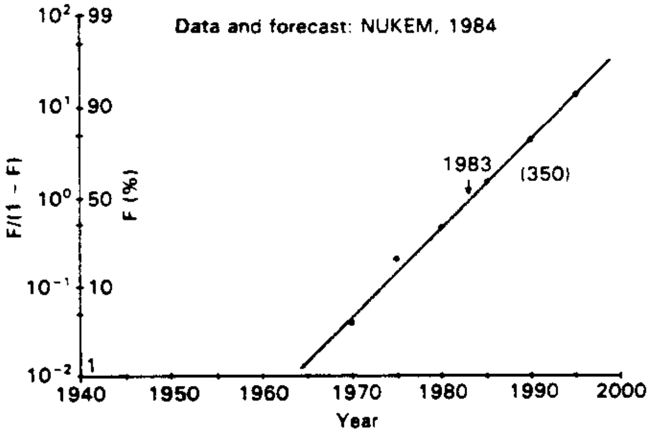

Fig. 3. Installed nuclear power plants (in gigawatts) in the western world.

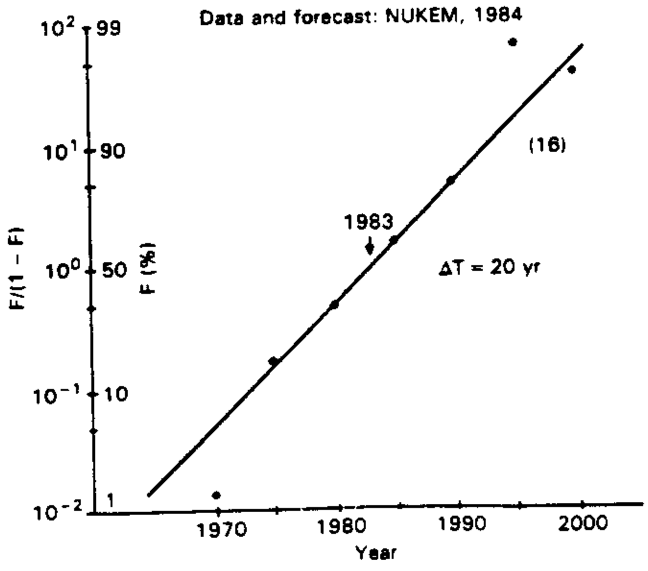

Fig. 4. Installed nuclear power plants (in gigawatts) in

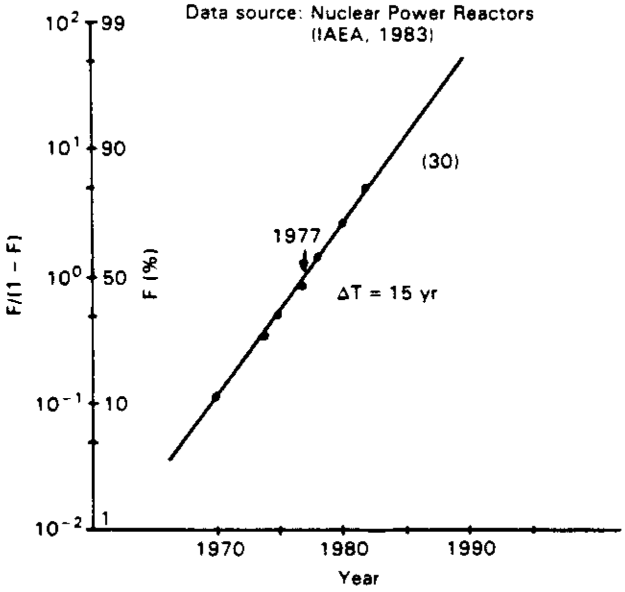

Fig. 5. Number of nuclear power plants in Japan connected to the grid.

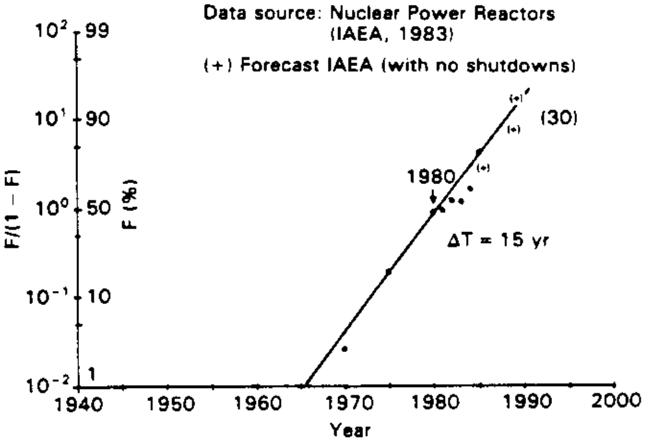

Fig. 6. Nuclear power plants (in gigawatts) in Japan connected to the grid.

curves can be used predictively. In such cases, the International Atomic Energy Agency's (IAEA) forecasts did and do appear excessively optimistic, but the prospects of doom also seem to be unfounded. Not only does nuclear energy proceed *in fact* along a standard course of development, but it penetrates the energy market at a much faster rate than one could expect from the previous penetration of coal, oil, and gas (Fig. 1).

Analysis of many industries through the centuries shows that the logistics are born and saturated within "time bins" of ~55 years, reminiscent of Kondratieff cycles. Our bin ends in 1995. After that the system may well start a new wave of growth (or be reabsorbed in a downward wave). For nuclear energy this may

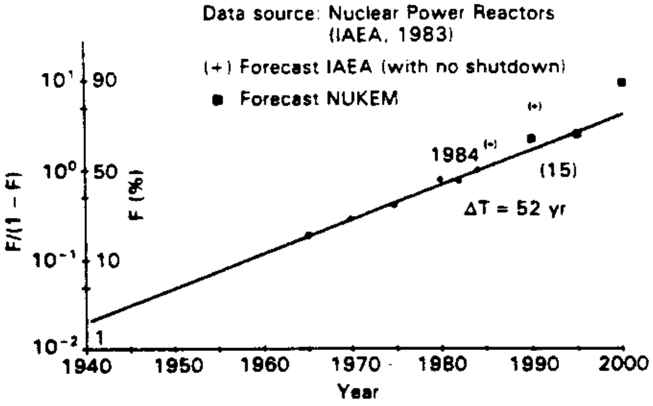

Fig. 7. Nuclear power plants (in gigawatts) in the United Kingdom connected to the grid.

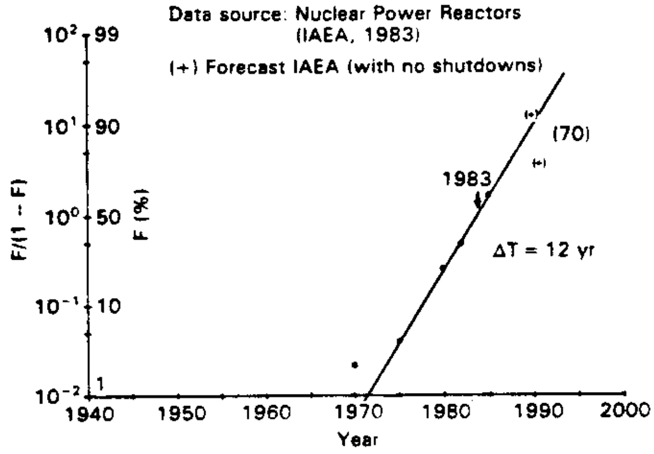

Fig. 8. Nuclear power plants (in gigawatts) in France connected to the grid.

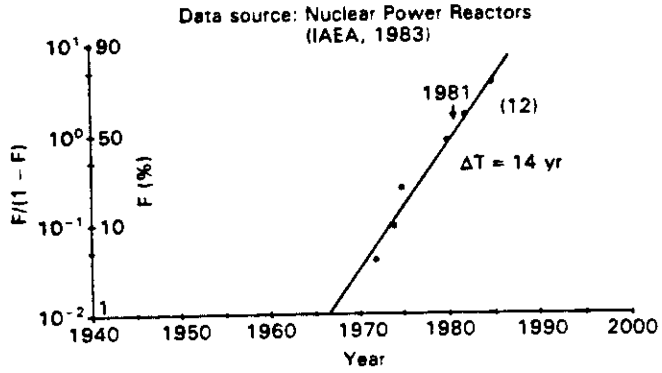

Fig. 9. Nuclear power plants (in gigawatts) in Sweden.

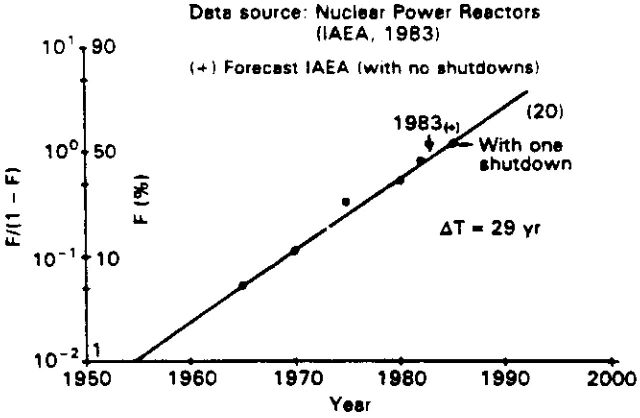

Fig. 10. Number of nuclear power plants in Sweden connected to the grid.

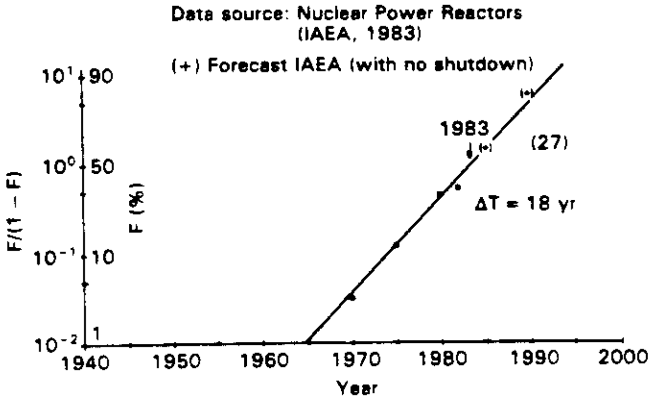

Fig. 11. Nuclear power plants (in gigawatts) in the Federal Republic of Germany.

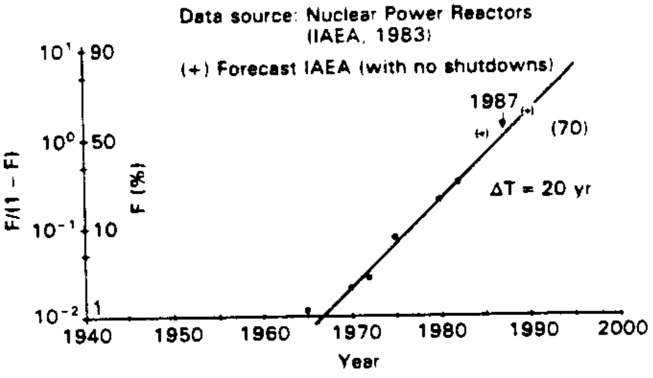

Fig. 12. Nuclear power plants (in gigawatts) in the USSR connected to the grid.

well depend on the technical ability to open nuclear energy to the nonelectric market.

The analysis of natural gas penetration in countries

gas shows a behavior similar to nuclear, gas penetrating at a very fast rate at the beginning, and then slowing to a more "normal" rate, i.e., analogous to that for oil in the same country. The interpretation has

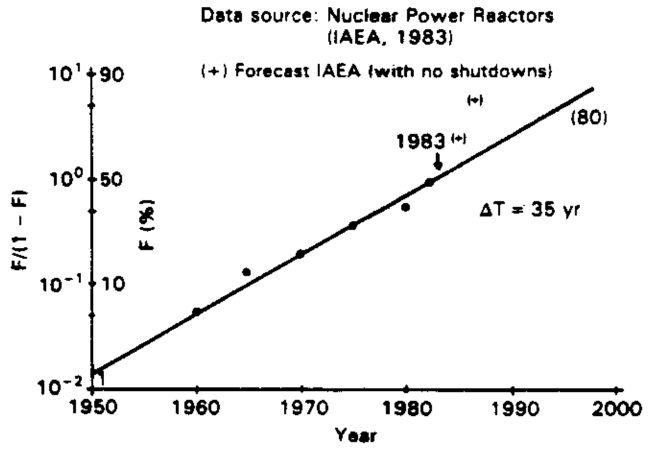

Fig. 13. Number of nuclear power plants in the USSR connected to the grid.

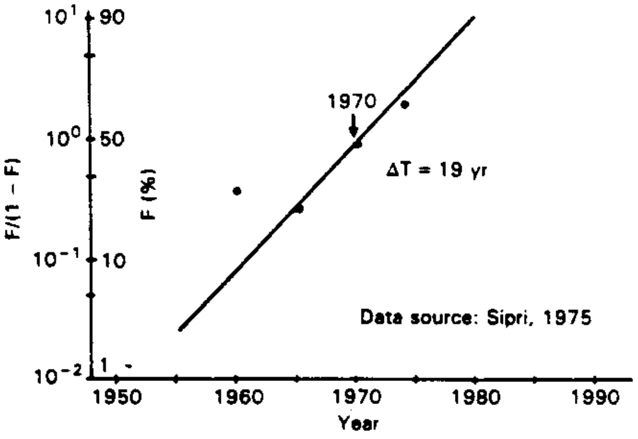

Fig. 14. U.S. patrol submarines, nuclear versus conventional.

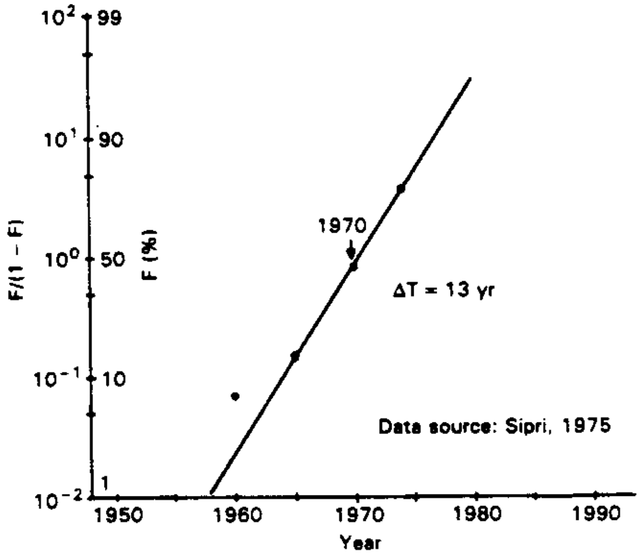

Fig. 15. USSR strategic submarines, nuclear versus conventional (the United States is 100% nuclear).

been of two different niches, one where substitution could be done at the level of the network, and the other where the final consumer must be reached through a new network, obviously a more cumbersome operation.

In the case of nuclear energy, the electric network is the equivalent of the city natural gas network. It may not take long to saturate, at least in some areas, such as France, Switzerland, Sweden, Bulgaria, as well as Great Britain, Germany, and Japan. In such places the penetration of nuclear energy as a substitute for fossil primary energies will soon slow to a crawl and perhaps even stop, thus denying the original promise of nuclear energy to become the sole source of energy, which would have finally liberated human beings from the danger and lethality of digging for fossil fuels.

The only way to retrieve the situation is to create a new network to bring nuclear energy to the final consumer, and the most appropriate recipe for that seems to me to split water to produce hydrogen.

Because the question of expanding beyond electricity is so vital for the next round of nuclear energy penetration, and because my analyses show that revolutions are the tip of evolutionary icebergs, I will show here the curious results of an analysis of the historical evolution in the composition of fossil fuels, indexed by the hydrogen/carbon (H/C) ratio (Fig. 16). During the last 200 years, the fuel mix evolved toward "lighter" forms, i.e., richer in hydrogen, and although this is a trivial observation, it did it in an extremely regular way. By using the logistic of Fig. 16 in a predictive mode, we can forecast when "external" hydrogen, i.e., hydrogen from water, will be in demand in the fuel system. It is toward the end of the century,[3] just at the start of a new round of nuclear reactors, perhaps signaling the beginning of the second nuclear age.

Returning to Figs. 2 through 13, a beautiful regularity is shown in the penetration of nuclear energy. As a fact, this penetration cannot be challenged. I dare to add that the predictive mode carries a sedate but optimistic message. And this message will be very optimistic if we can solve the problem of producing hydrogen as a second energy vector, which I certainly believe we can.

These ideas have been much discussed during the last 15 years, and a lot of work done in the area. Dr. Weinberg has kept an interested eye on the debate over and the progress of this concept. [One of Dr. Weinberg's ideas was to suggest the use of pressurized water reactors to power strategic submarines. I looked at the penetration of this new technology into military fleets (Figs. 14 and 15). Contrary to current opinion, the way the military uses these concepts seems very similar to that of industry.]

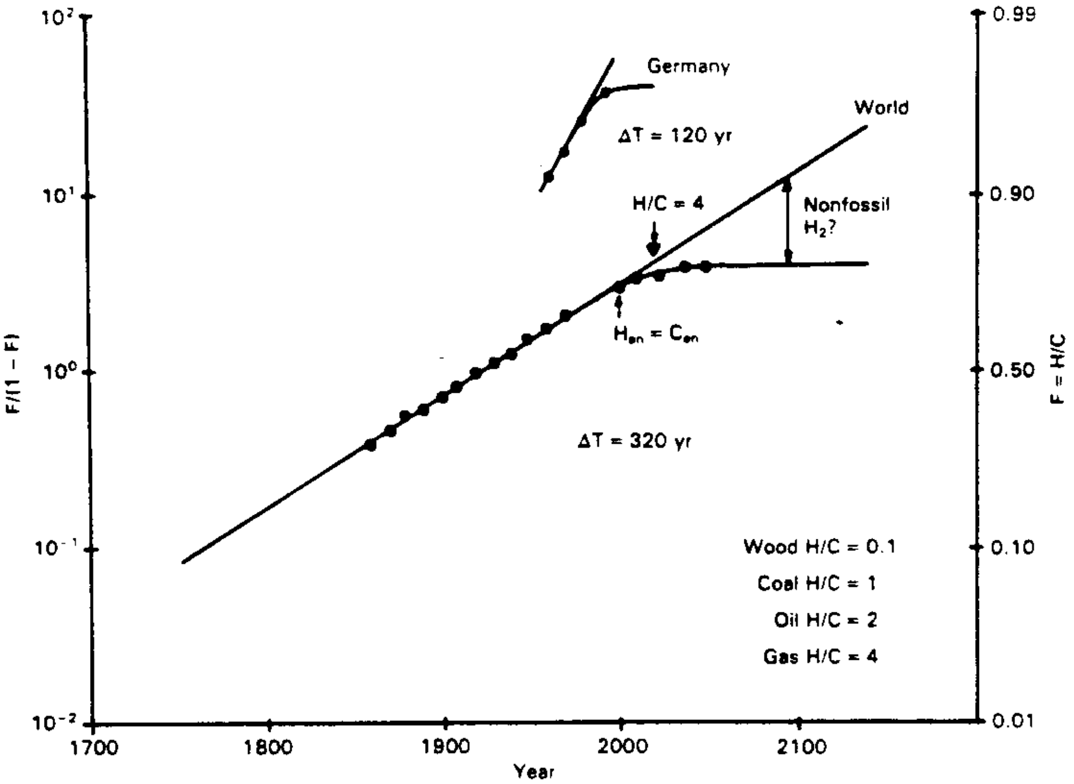

Fig. 16. Using the data from Fig. 1, the H/C ratio in the primary fuel mix has been calculated and fitted in the same way. The points and the curve after the year 2000 have been calculated using the mix given by the equations of Fig. 1. As the sources here analyzed are primary, the energy to produce the hydrogen in the gap should not be fossil. For simplicity, the line after the calculated points has been drawn horizontally at the level H/C = 4, but it should curve down due to the progressively reduced contribution of natural gas after 2030.

APPENDIX

For the growth into a niche of unknown size, the data are fitted to the equation $\log[N/(\bar{N} - N)] = at + b$.

The best fit to a straight line produces $\bar{N}$, the final number of reactors (or gigawatts), a giving the spread in time of their installation and b a time cursor locating the process in calendar time. The charts are normalized by using $F = N/\bar{N}$. The niche then always has the size of one.

For the competition between two structures, as in Fig. 16, the niche is taken as equal to their sum, and in any case its size is eliminated by looking at their ratio. For a more complex case such as in Fig. 1, the analytical technique and the computer package are reported in Marchetti and Nakicenovic.[4]

The saturation point $\bar{N}$ is given in parentheses with the appropriate units. The time constant ΔT is the time for N to go from 10 to 90% of $\bar{N}$.

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