Energy Supply:
The Long-Time Horizon

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February 1997

For a presentation at the Conference *Energy and the Greenhouse Issue.*
ABB/IEA GHG Forum, 3 March 1997, Baden-Dättwil

Since man started burning wood (and woods) energy supply has been ambiguously abundant. Humanity is now consuming about 10^{10} tons of coal equivalent per year (better 10 TW) and forests shed, as "biomass" in form of leaves, branches, and dead trees, about 100 TW. A factor of ten larger than the consumption of humanity.

In actuarial terms then, why did we move out of wood. One can say because the 10 TW are here and there around the world. But considering that more than 50% of the traffic over the oceans is taken by oil, we could certainly say the same for oil.

Actually, as I will show, the shift from a primary energy to the next is linked to technological and economic pulses *inside* society, and that primary energy sources to date – wood+hay, coal, oil, gas (and fission nuclear) – will be finally abandoned without exhausting the available resources.

The solution to the problem I found already in the mid-1970s, in the middle of a fake energy crisis, when I was asked precisely the question in the title. My relaxing answer, however, is certainly less creative than the hypothesis of an impending shortage, and shortage was actually the hypothesis that received most attention, research, and funds.

My point is very simple: energy products should be treated just as any other product on the market. It is true that they are very important, but also construction materials are equally important. So let us apply the rules of the market to them and see what happens.

A simple way is to look at the dynamics of substitution. Every product has a starting date, a market penetration, and a market phase-out: *the product life cycle.* Applying the idea to primary energies, we find that the model fits very well the time dynamics of market shares, for the last couple of centuries.

What distinguishes primary energies from other products are the extremely long life cycles – 250 ÷ 300 years – which give a sense of immobility when observing them over short periods, 10 or 20 years, which is the time span usually covered by economic considerations. The very long life cycle gives also a very long time constant in the management of resources, basically the search to discover them. Because this search is usually very expensive, the system stops searching when the appropriate reserve level is met for optimizing exploitation and amortization costs.

In the set of figures accompanying this test I report an old chart compiled by King Hubbard on total amount of oil extracted, and total amount of oil identified as available reserves, in the United States. The chart is paradigmatic. It shows the two curves moving in parallel, that of reserves preceding by 14 years that of consumption.

Certainly, one can make a specially large strike, or stumble in an area where discovering oil costs almost nothing. But in the case of the United States, where finding oil is difficult, the game was played following the rules. And for the 80 years covered by the chart the extent of reserves was stable over the 14 years of current consumption.

The alarm cries that we have reserves only for 30 years, one of the many figures I have seen around for oil and gas, mean to my ears that somebody has overspent in research, or that somebody has been excessively lucky. I can be jealous or critical, but not concerned. Anyway, the future abundance comes from the fact that most promising areas are basically unexplored.

The market life cycle of primary energies shows an incredible stability in its evolution, through economic crises and wars, and explicitate the inherent stability of social processes we have evinced in thousands of analyses done with the same methodology.

If a deviation occurs we may expect forces driving it back to the canonical course which appears to be a kind of attractor. E.g., coal runs now above the secular equation of its life cycle and natural gas below. It is well known that this is due to coal sticking to electricity production in Germany, the UK, and the USA.

The forces calling back to the "appropriate" course are CO_2 emissions (US) and short public money which kept the coal pits open. Miners demonstrations in the Ruhr are a clear signal of the process. Certainly these movements are very slow, but they have to be measured against the very long life cycles.

The straight analysis of life cycles requires a cycle to be started in order to fit the appropriate equation. Consequently, forecasting cannot go too far (e.g., only 50 years) because an (unexpected) newcomer (e.g., nuclear) may enter the market upsetting the previous dynamic of substitution, if slowly. But a new primary energy can also be considered a technological innovation, and a basic one by the way. So the analysis on how basic innovations are introduced in the market may throw some light on the coming times of newcomers, and thus make even longer-range forecasting possible.

In fact, basic innovations come in waves, quite symmetrical, whose centerpoints are spaced about 55 years. New primary energies seem to prefer the beginning of a wave as a starting point in time. These innovation waves have many internal regularities that permit forecasting them. So for coal, oil, and gas, they were carried by the three previous waves. The fourth one, centered in 1993, has the beginning of its tail in the mid-1970s where commercial nuclear energy was born (innovation dates always refer to their first commercialization).

The coincidence may appear magic if we consider all the improbable coincidences that led to nuclear energy. As a systems analyst I could write a thick book on "Systems Black Magic". The famous "invisible hand" could well be rebaptized the "invisible steel hand". Anyway, following these rules a new primary energy should pop up, commercially, around 2025.

The last primary energy in the series is nuclear, and it is very young. More or less 20 years, or less than 10% of the product life cycle. Worrying tutors are saying everything plus or minus, but at a second look it is clear that they talk about their emotions.

It is a common say, e.g., that nuclear energy is a closed experiment, like communism, because it is too dangerous and people do not like it. However, if we look at what happens to innovations, after they took off from the innovation wave, we see that they penetrate logistically into the market and saturate at the end of the 55 year cycle (~1996 for the present one).

Inevitably, not only nuclear plants, but also cars, dishwashers, and GNPs saturated more or less around 1996. As everything else by the way, which is the definition of recession. It should be said then, for coherence, that there will be no restart for them, because they are too dangerous and people do not like them. Or for other opportunistic reasons.

It must be clear that also the growth of coal and oil can be broken in logistic slots of 55 years length, reconfirming that the world did not change for the sake of nuclear energy. Consequently, in the philosophy of business-as-usual we may well expect a resurgence of nuclear plants building just after the year 2000.

The dominant primary energy, however, during the next 50 years, will be natural gas, and for that reason some years ago I proposed a marriage that should have brought to solution at the same time the problem of CO_2 emissions and that of piping nuclear energy into the chemical fuels pipelines. The proposal is described in some detail in the associated figures.

As my presentation refers to energy resources, how long can nuclear energy last? Nuclear energy at present comes following three concepts:

1. Fission centered on U^{235}, with enriched fuels if necessary, and Pu where possible.

2. Fission centered on (fast) breeding, where most of the fissionable atoms are burnt, be they U or Th and their products.

3. Assisted fission where an external source of neutrons, e.g., in form of an accelerator-spallator, is introduced.

Reactors of type (1) burn a few percent of the original uranium and thus require a lot of it at fairly low prices. No problems for present or the next 20 years. But the long run requires a theory of the interaction between man and minerals so that projections can be done.

An attempt in this direction was done in the 1960s at Euratom by Brink et al. They considered mineral deposits as distributed lognormal in concentration *and* in size. Mining results from a stochastic human attack to the mineral system with boundary conditions deriving from mining economics.

The actual mining industry can be taken as a sample, and from the sample the whole system can be reconstructed. The final result of the exercise is a curve giving the (secular) cost of extraction (relative) versus the amount historically extracted.

Applying the methodology, hindsightwise, to current metals, historical data are fitted quite well, if we think of the brutal simplifications. The key parameter defining the long-term evolution of price is concentration versus size of deposits. If size of mineral deposits does not grow much when going to lower concentrations, the cost of the metal tends to grow with the extracted amount (for example, gold).

For copper size of deposits grows fast enough to compensate for the lower grade thanks to economies of scale in mining and processing. So its price (relative) tends to be constant in time. Uranium is very similar to copper, so its price should stay constant even if millions of tons are extracted.

So procedure (1) may have a future. However, because a progressive increase of uranium prices, speculation apart, will be a very slow process, there is time to implement technologies (2) and (3) where everything is burned down, even the "ashes".

Procedure (3) was studied quite extensively under the leadership of Dr. Lewis in Canada in the 1960s under the code name ING (Intensive Newton Generator). Now the idea has been picked up by Prof. Rubbia at CERN that enjoys 30 extra years in accelerator development. I made him jump, however, when I said 1 amp and 1 GW were necessary to fit the appropriate size of power plants in the future (5 GWe).

However, sidelines are possible. When I was studying energy systems by and large in the 1970s, I got free rein from the boss, Prof. Häfele, to invent the possible, even if at the time it looked improbable. In this line I proposed the "Energy Island", an up to 10 TW nuclear complex, to be located on the sea as it obviously requires a lot of cooling.

As such a structure is to be seen in the time horizon of 50–100 years, I took care of all details ensuring ecological unobtrusivity and long-term solution of the energy problem. The energy is carried away by tankers in form of LH_2. The cooling water is pumped (automatically using water ΔT) from the depth ($\sim$500 m) and is released at sea surface temperature. There would then be no hot spot. Not negligible, because 1 TW is equivalent to more or less the oil production of the Middle East.

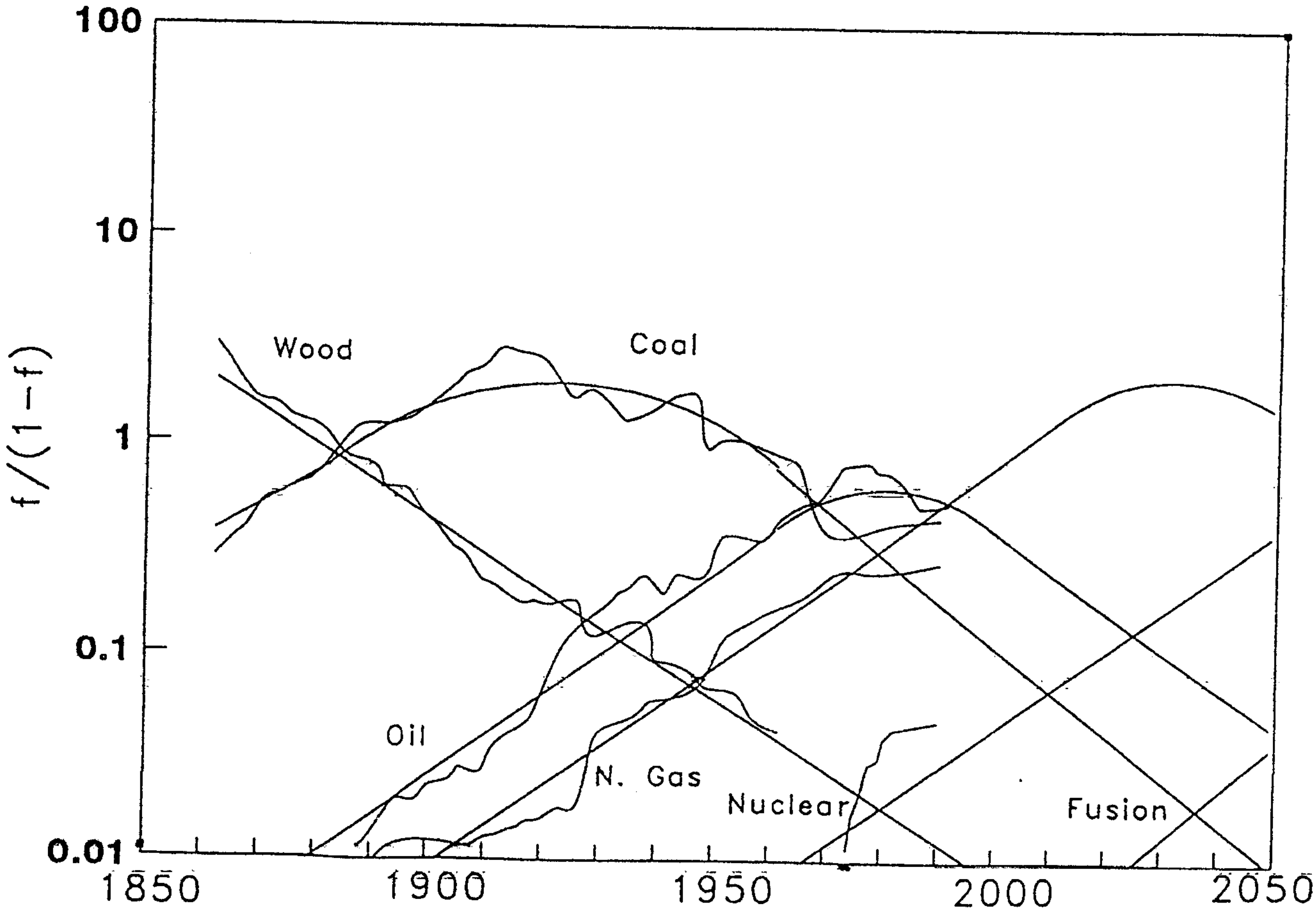
The more interesting point to our subject is that I adopted some sort of breeder reactor (200 GWth apiece), and observing that the uranium dissolved in the cooling seawater is an order of magnitude of that fissioned in the reactors I also proposed to extract it in the lagoon of the island (the atoll of Canton Island was my guinea pig).

MITI which I catechized in 1973, kept working since then both in U-extraction from sea water (with chemical absorbants) and on thermochemical watersplitting (UT-3) reaching now quite feasible designs for both. Because the waters of the Pacific overturn in about 2000 years, I actually invented a primary energy source lasting 2000 years, at least (incidentally the oceans contain about 4.5×10^9 T of U in solution).

I can then conclude here the question of resources, saying that the problem of providing energy to humanity "c'est un problème d'intendance" where technology, adaptation, and wisdom can solve all the problems as they come. However, this does not mean that the "Energy Island" will be the final configuration.

If we go back to our innovation game, a new primary energy is on call around 2025 and another one around 2080. For the first, one could bet on fusion. Fusion technology is poking ahead, but the progress is visible. One of the advantages in my opinion is the potential for very large machines, in terms of unit power, which will fit the scale of demand.

For the second one, during a speech I gave at CERN, I proposed to these supreme physicists to come back to social and find a way to squeeze energy out of more or less elementary particles. Out of the fast thinking silence a voice said: "If only the proton had a shorter life". Well I said, death can be catalyzed. The half-life of U235 can be annihilated in the blitz of a nuclear bomb. *Never drop hope.*



Logistic substitution of primary sources by the MN method in the period 1860–1990.

Figure 1.

This is an old chart (1975), rejuvenated to 1990, showing the evolution of market shares (F) for the primary energies, expressed in energy units. The smooth lines are the fitting of a multiple competition model, of ecological descent, extremely sober mathematically, as only two parameters need to be fixed to describe all the life cycle of a primary energy. By and large, the fitting is good and shows a great long-term stability in the substitution. The recent deviation of coal and gas is the indication of an insufficient substitution of coal with gas in electricity production. Coal extraction in the USA, the UK, and Germany is bound to very viscous social constraints.

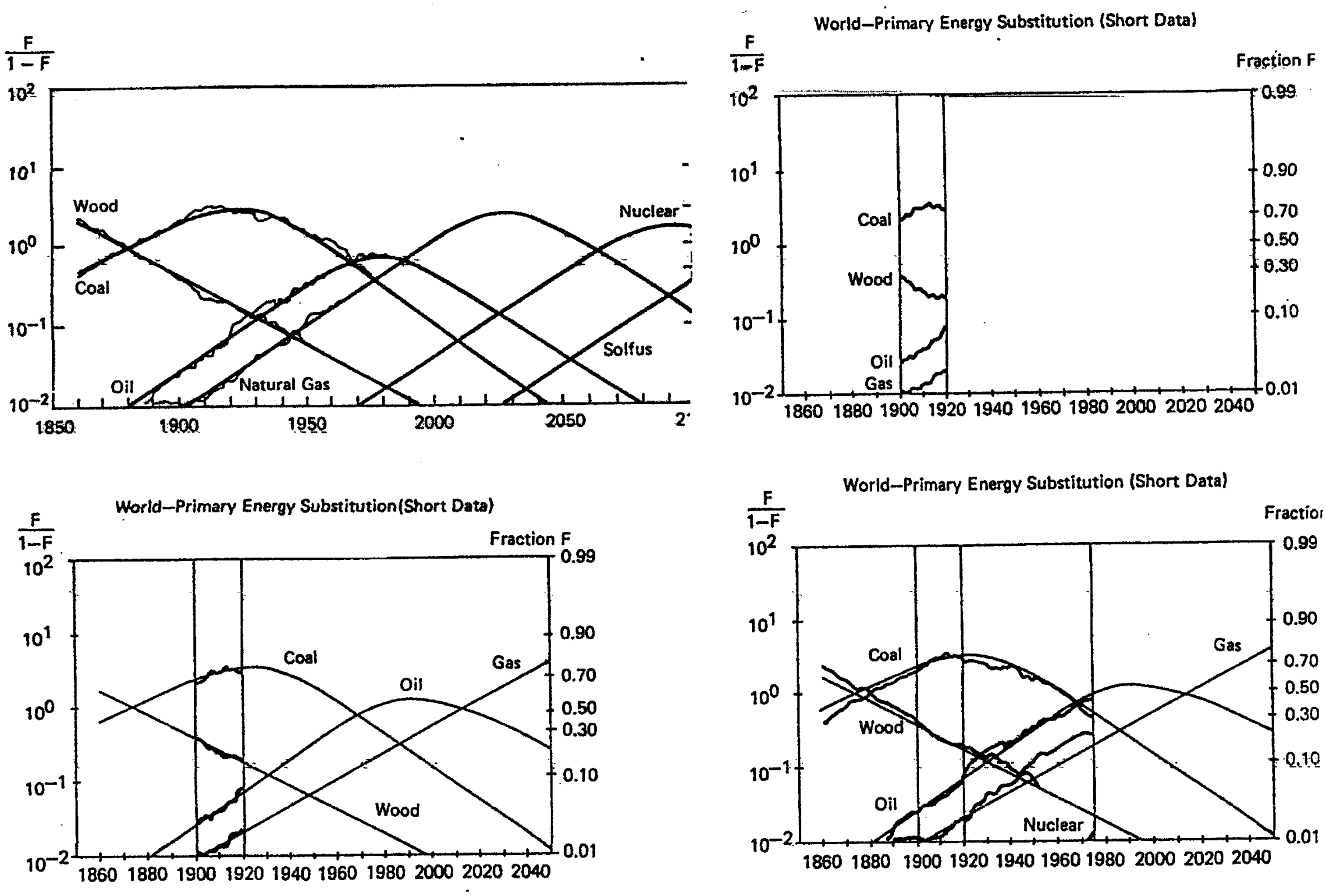


Figure 2.

Using the set of equations that describe the interactive life cycles of competing products (primary energies) it is easy to forecast up to about 50 years the evolution of the shares. This under the hypothesis that no new competitor is coming in. In the example given here the equations are fitted in the period 1900–1920, and their forecasting capacity is tested for the period 1920–1970. However, longer periods are not possible due to the interference of new competitors. A way out of the impasse is described in the next figures.

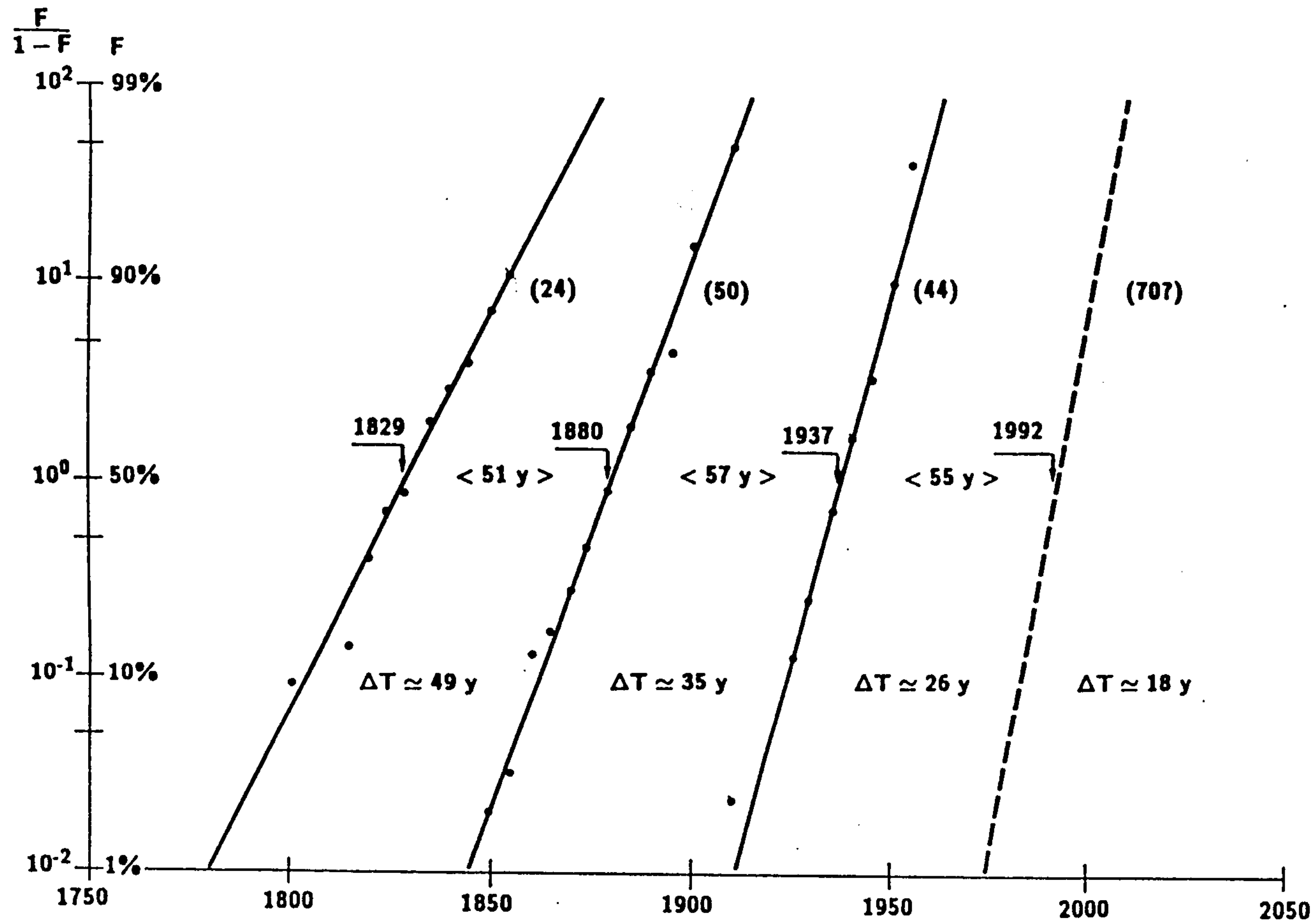


Figure 3.

Innovation waves, here reported as cumulative number of *basic* innovations (Mensch), show a periodicity of about 55 years. This and other quantitative relations make them predictable. In our context it seems that a new primary energy is introduced in synchrony with a new innovation wave, just at its beginning.

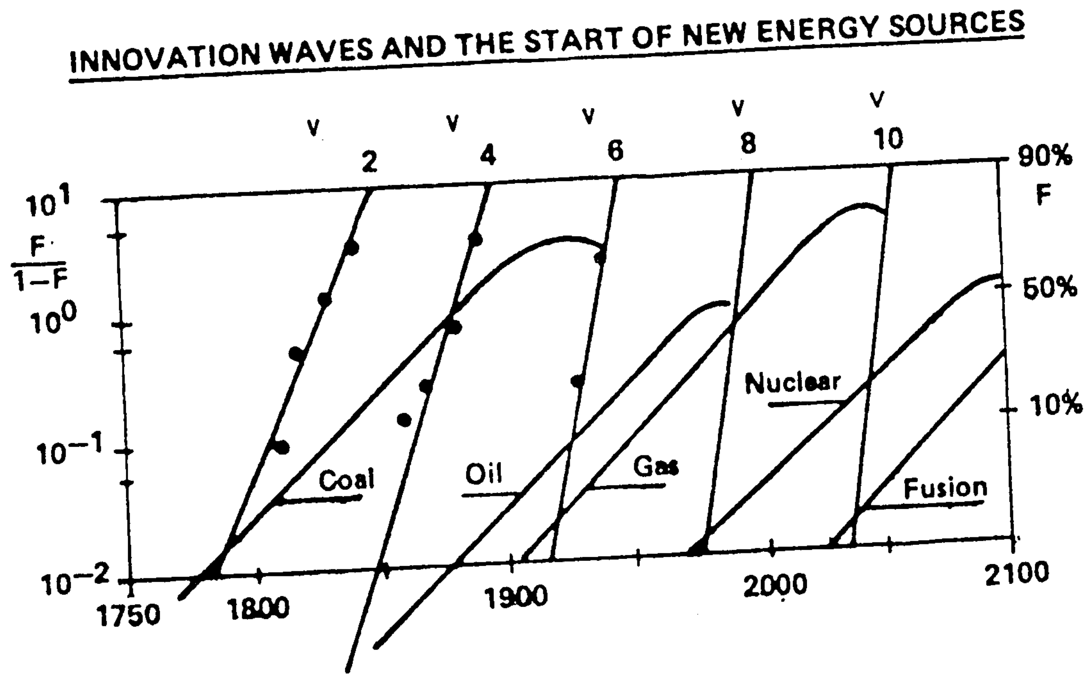


Figure 4.

The superposition of innovation waves and start branches of primary energy penetration are reported here. Because innovation waves can be predicted, we can allocated also time windows to the introduction of new primary energy sources, around 2025 (shown) and around 2080 (not shown). This analysis does not permit to see what kind of primary energies we are going to have. In 2025 it is presumably going to be fusion. The present innovation wave is also "predicted" because it can be verified only post fact (~ in 2010). The coincidence of the starting point of nuclear and that of the wave appears very good.

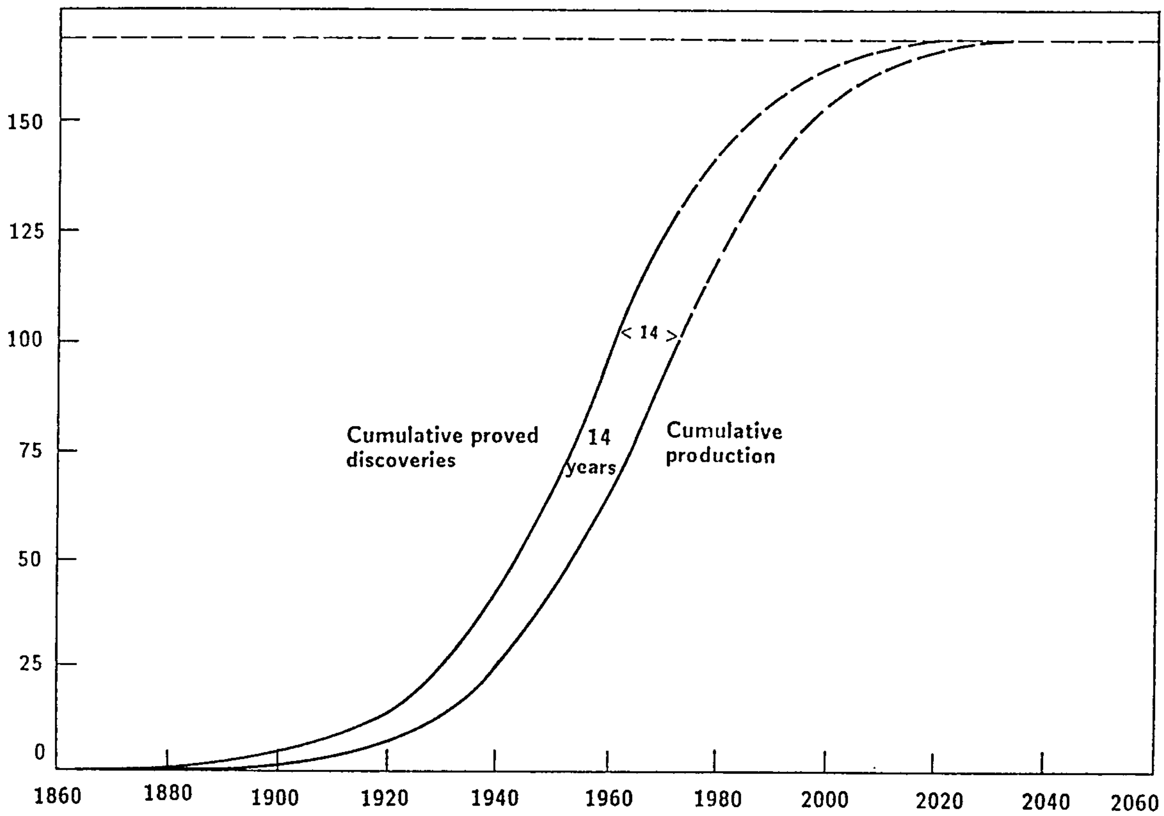


Figure 5.

As said in the text, there is no direct connection between availability of a certain primary resource and its phase-out in terms of life cycle. And usually there is no serious estimate of the future availability. Actual reserves are born by the activity of prospectors, wild catters for oil and gas, which is limited by *demand* for new reserves. This seems to activate when reserves go below about 14 years of current consumption, as shown in this graph for the USA, redrawn from King Hubbart. This level of reserves can be explained by minimization of extractive costs, including interests and amortization, on top of research costs.

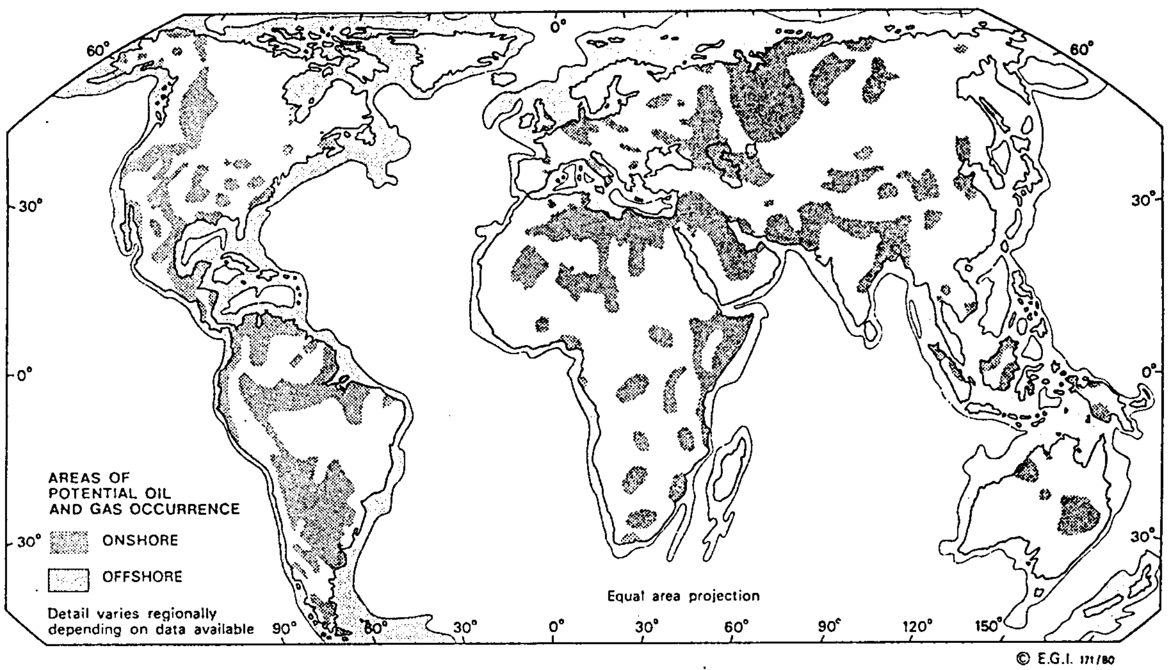
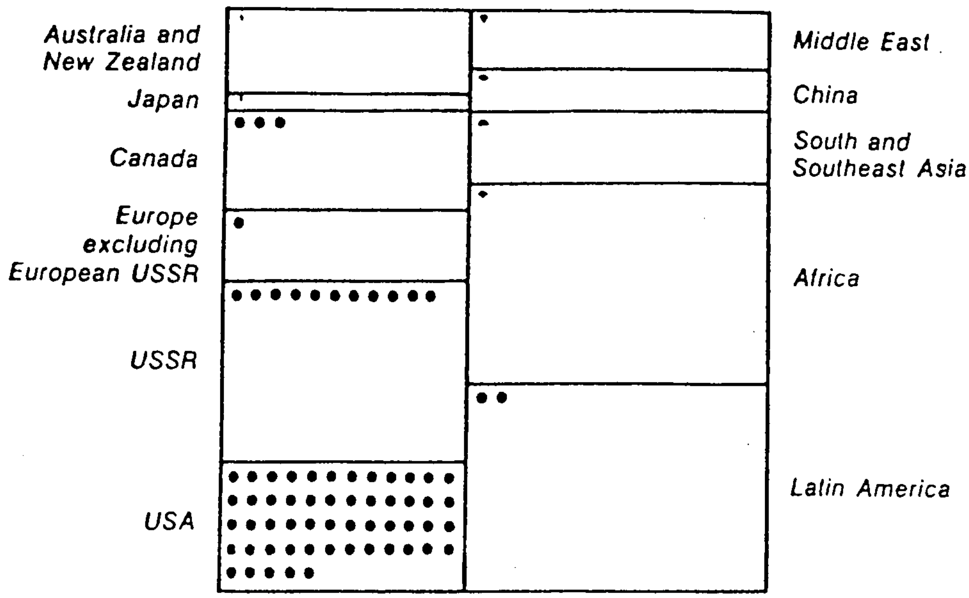


Figure 6.

This chart shows promising areas for oil and gas reservoirs. They are based on general considerations, and altogether very little explored (<1% in volume). Actually, geological theories do not permit the initial identification of reservoirs, a task usually left to the nose (the physical one) of wild catters. Geology then helps by following the structures, and physical tools to identify possible reservoir rocks.



The best measure for assessing exploration efforts in various petroliferous areas is to map the level of perforation against the extension of the area itself. *Source:* Grossling [1].

Drilling Finding Rates (Tons per Meter of Exploratory Well)

Year	USA	Western Europe	Latin America	Africa
1970–1974	7	520	200	520
1960–1964	6	17	57	380
1950–1954	7	40	80	37

Source: Grossling [1].

Figure 7.

In 1976 Grossling made these two charts, showing the situation to date of drilling for oil and finding oil, showing that outside the USA it is easy to find new oil, as the promising areas are little explored. The second chart shows the amount of exploration versus the size of the promising areas in various continents. The volume explored in the USA is about 2% of the total interesting. The two charts certainly need a (very laborious) updating, but except for the North Sea, nothing really striking happened since then.

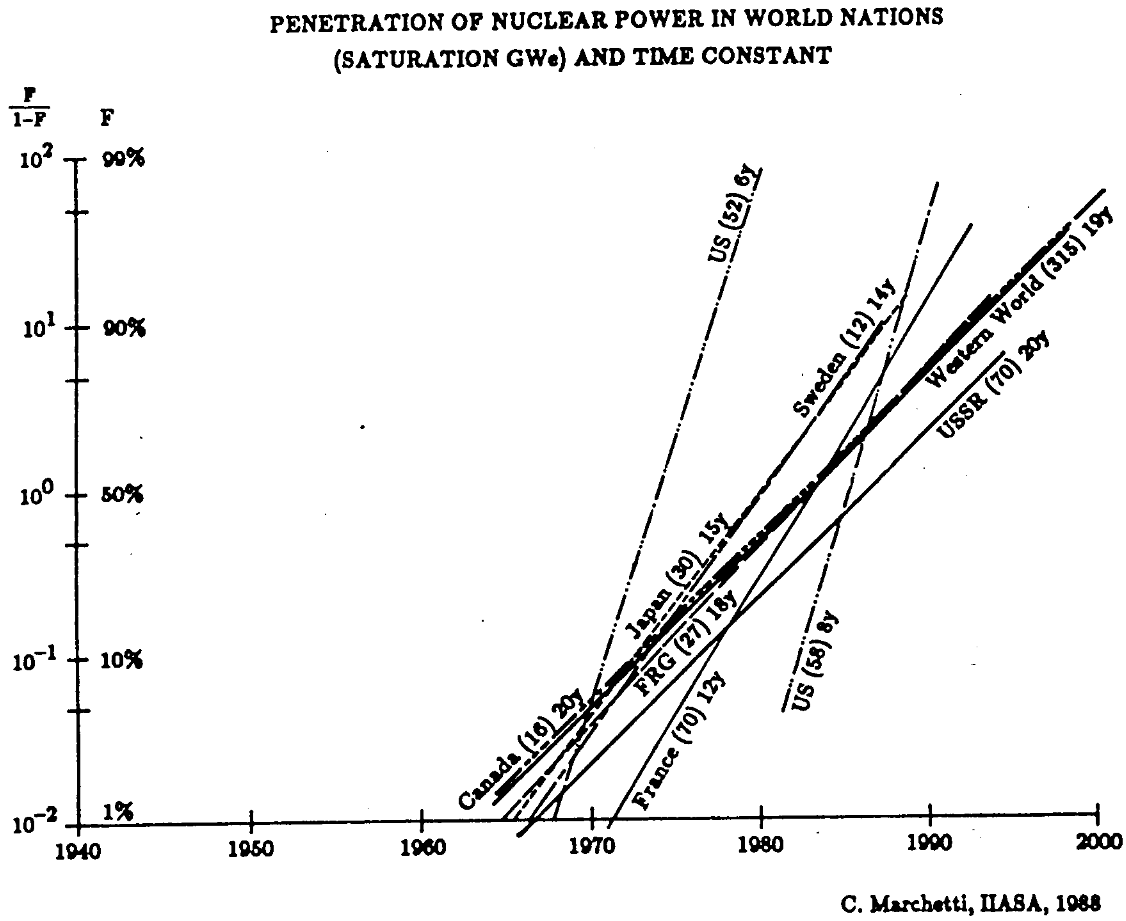


Figure 8.

Many people give the nuclear experiment as a close one. In our conceptual context, this is absolutely not the case. Economic growth appears to come in pulses of about 55 years, half happy (boom), half sad (recession), most activities (and GNP too!) grow in logistic pulses, saturating toward the end of the cycle. This is also true for nuclear energy, which then follows in a sense a prescribed path. The end of the cycle is around 1995 and the re-start of nuclear construction should be just after the year 2000.

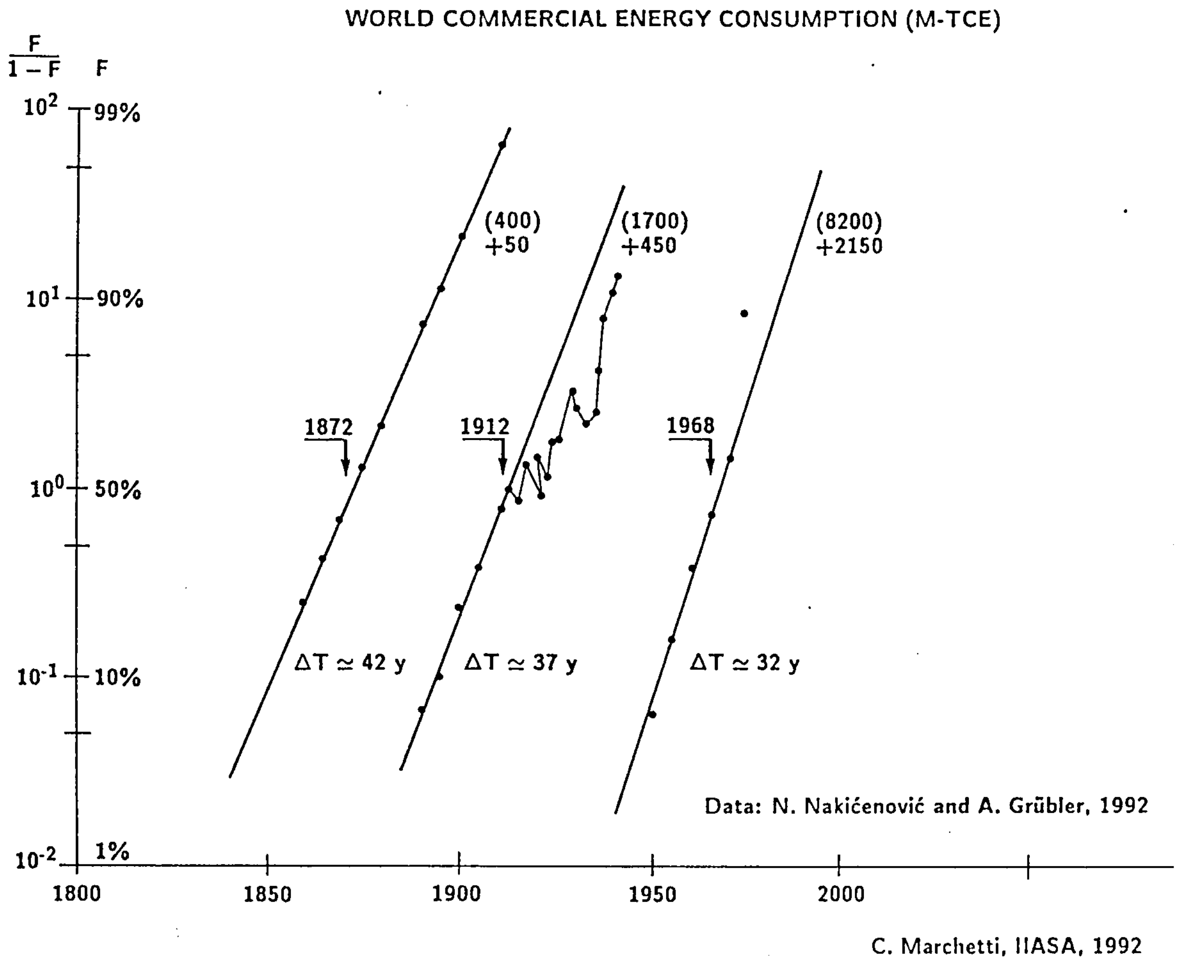


Figure 9.

The stop–go process is represented here for energy consumption as a whole during the last 120 years. The chart decomposes global energy consumption growth into three logistic pulses, each ending in tune with the end of the corresponding economic pulse (1885, 1940, 1995). As the + numbers show, the platform on which the pulse starts is given by the sum of the saturation points of the preceding pulses.

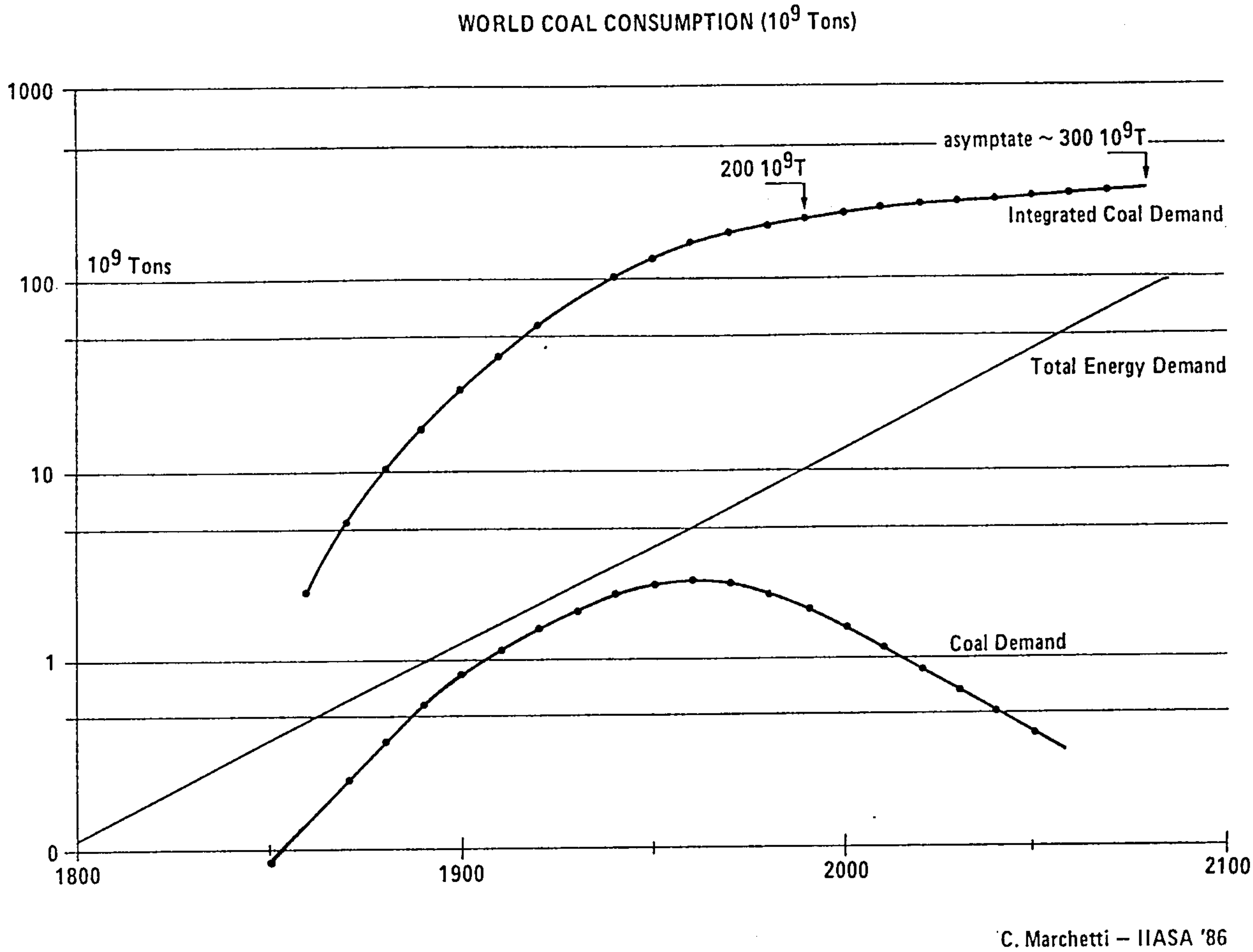
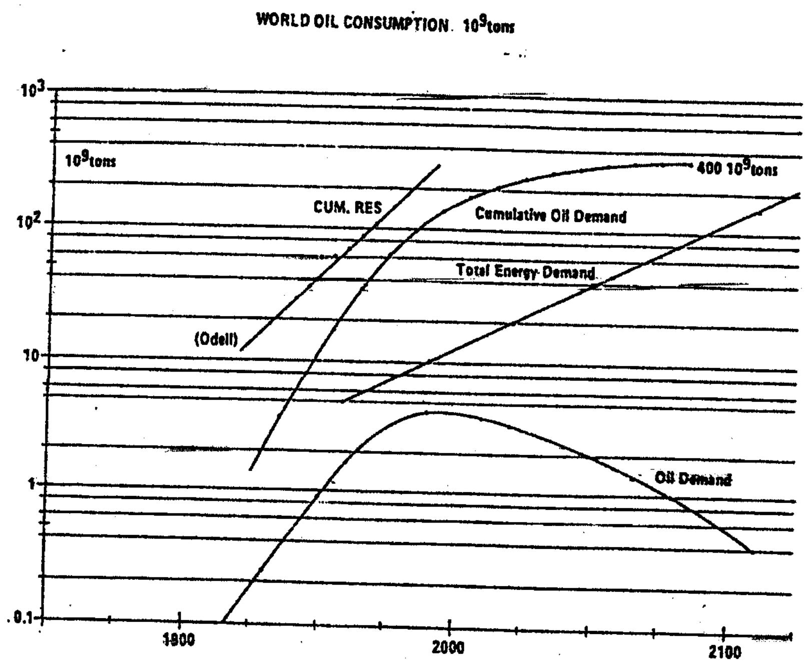
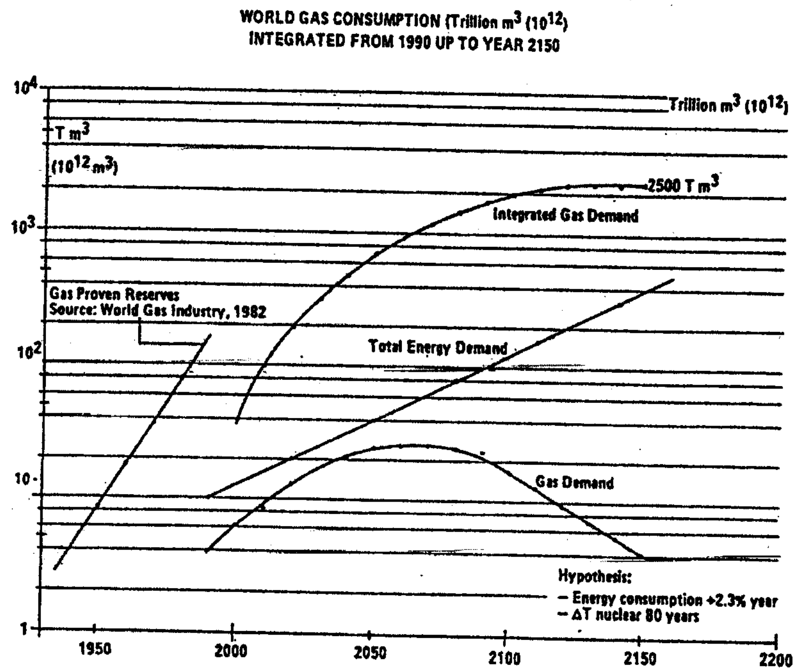


Figure 10.

Concerning *total* consumption I was *not* able to find a logic to forecast its evolution. During the last 200 years it had a growth, mean, of 2.3%. A zero option is to keep it constant, e.g., for the next 100 years. This means a ×10 increase, from 10 TW to 100 TW. Seen from another point of view, this would mean bringing the world population to Western levels today in one hundred years. Sounds plausible. In this hypothesis of growth we can easily calculate total demand, yearly or integrated, for any primary energy (except the last one). For coal the asymptote should be 300 10^9T, and we are now a little above 200. Ambientalists must still shed some tears. The curves are smoothed over the 55 years cycle, so there is no way of finding the consumption of a single year.



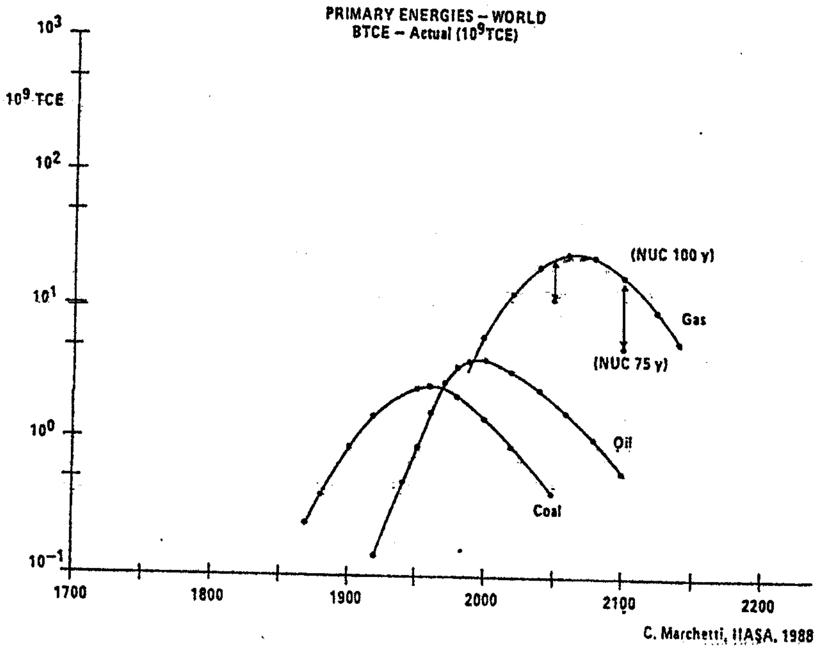
OIL



GAS

Figure 11.

As for coal, the same exercise can be done for oil and gas. However, because the final penetration of gas depends on the penetration rate of the next primary energy, nuclear, a hypothesis on the rate of penetration of nuclear is necessary. We took 80 years (the time to go from 1% to 50% of total primary energy). Together with the other hypothesis of world energy consumption growth of 2.3% per year we get for oil a final, integrated consumption of 400 10^9 tons and for gas 2.5 10^{15}m^3. The last number is huge and luckily natural gas seems to be everywhere, as a product of degasing of the earth mantle.



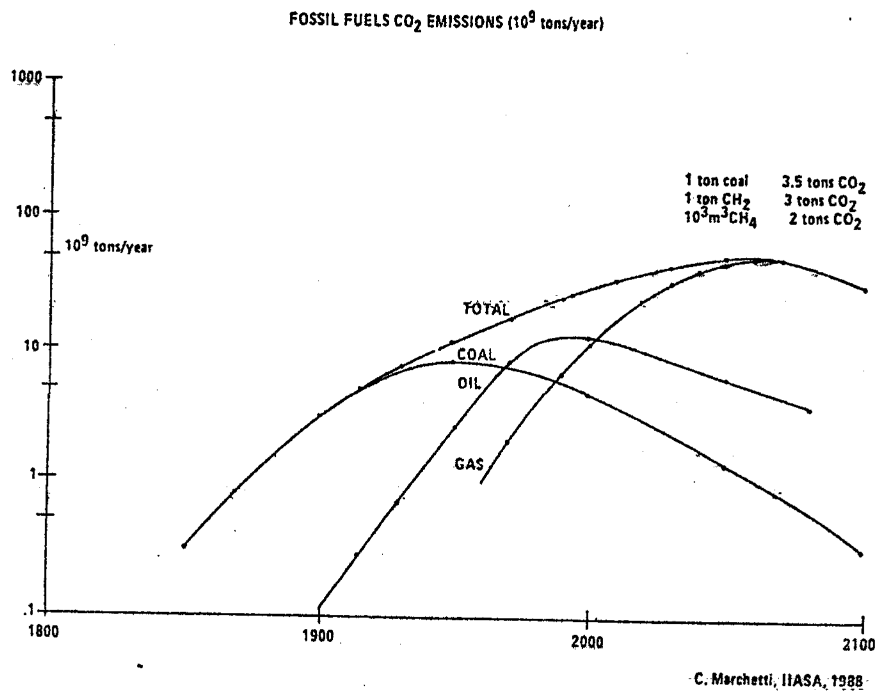


Figure 12.

The model, plus the hypothesis of 2.3% energy growth, makes it easy to forecast consumption of each primary energy and CO_2 emissions. For these we have also chosen 100 years for the characteristic time of penetration of nuclear, which defines the life cycle of natural gas.

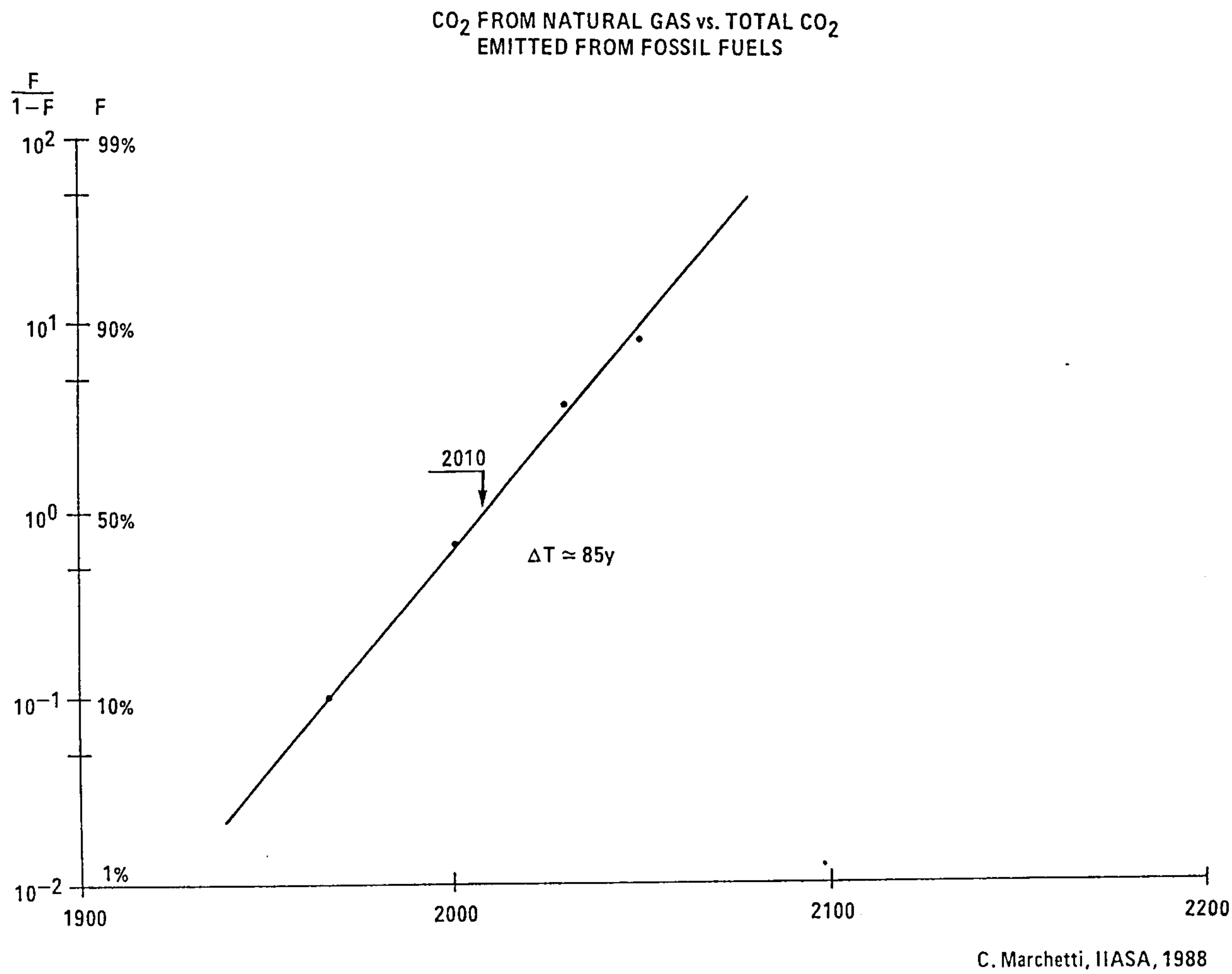
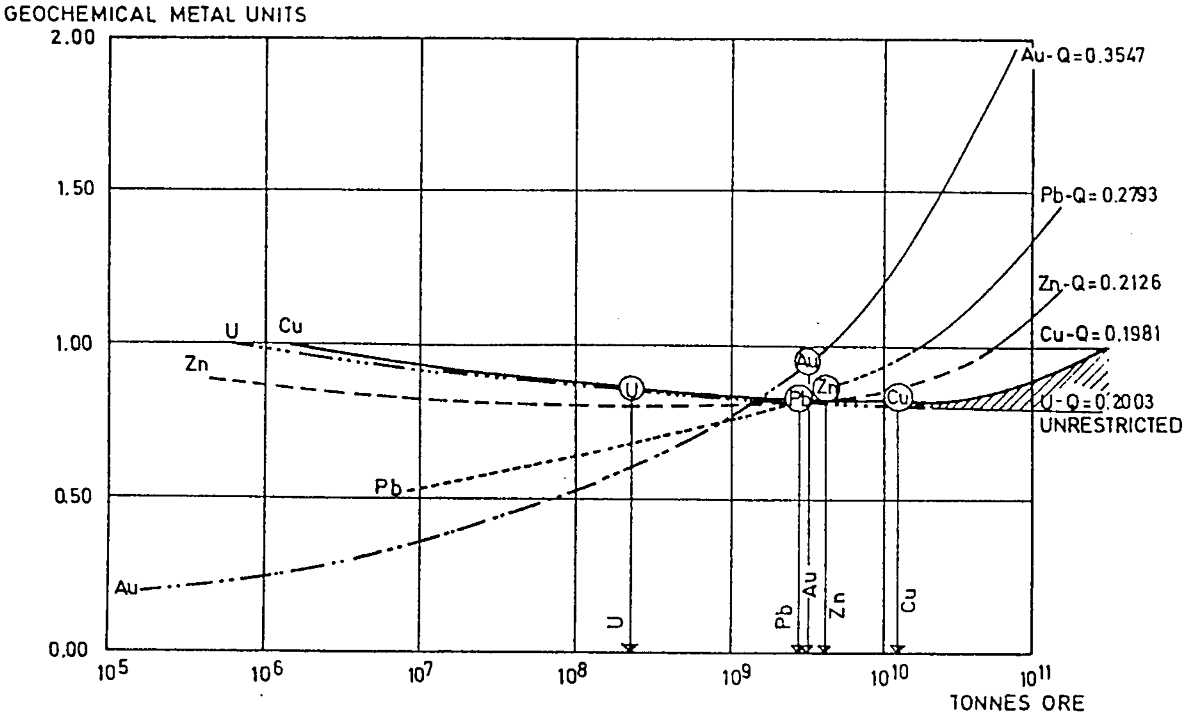


Figure 13.

The striking dominance of natural gas for the next fifty years means also most of the CO_2 will come from it. This is a particularly favorable situation, because NG transport is done in large chunks where a "refinery" to make H_2 and dispose CO_2 is easy to locate. I did a Gedankenexperiment, some years ago, to "refine" increasing fractions of the methane coming from Russia (about 50 $10^9 m^3$/year) using heat from HTR reactors, and disposing the CO_2 in exhausted oil fields nearby (Belorussia and Poland).



LONG TERM EVOLUTION OF THE PRICE Cu, U, Zn, Pb, Au

Figure 14.

The only attempt, to my knowledge, for a *predictive* theory of mineral resources, if statistical, was done by Brink et al., when working at Euratom in the Sixties. Assuming a certain distribution (lognormal) in ore bodies size *and* concentration, and sampling the distribution via the actual and historical mining activity, one can calculate the parameters and estimate extraction costs versus the amount extracted. Correct reading on the chart requires a number of long definitions. However, the raising of the curve indicates a raise in cost with the cumulative extraction of a certain metal (e.g., gold). For uranium there is no increase. These prices are relative between metals, and can actually decrease in absolute terms, with the evolution of the mining industry.

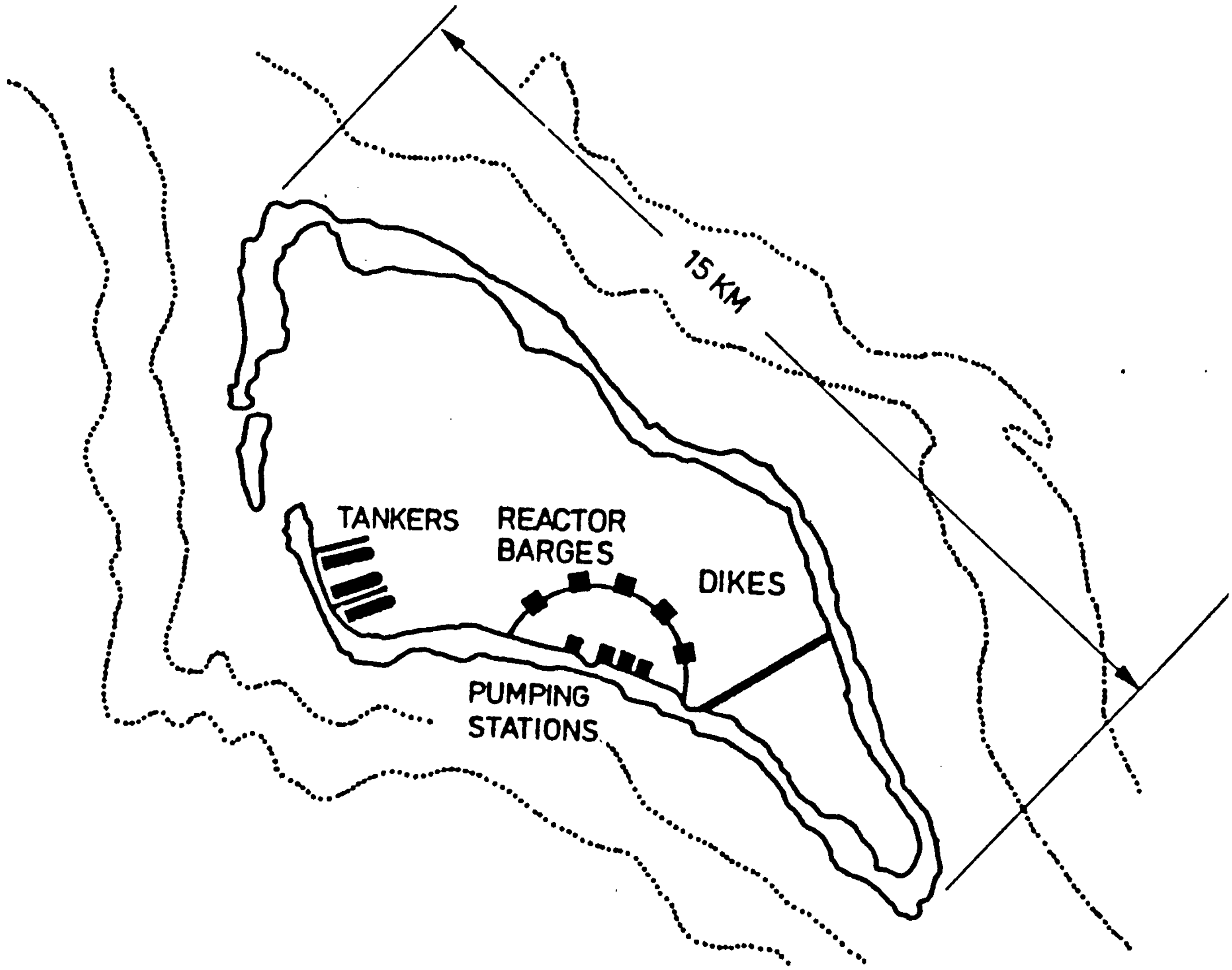


Figure 15.

In the long-term evolution of energy systems, nuclear sources of various denomination are the most likely sources of primary energy. They have the potential of being extremely compact and consequently cheap. Because the size of the energy producing unit is determined by spatial consumption and transportability, by choosing LH_2 as energy carrier, LH_2 tankers can span the world, as for oil. Consequently, the units can have a size of about 1/10 the global energy market basically to optimize for the standby. Thus, in 1970 I proposed energy islands producing LH_2 and having powers of the order of 1 TW, which fits the (1970+30) energy consumption.

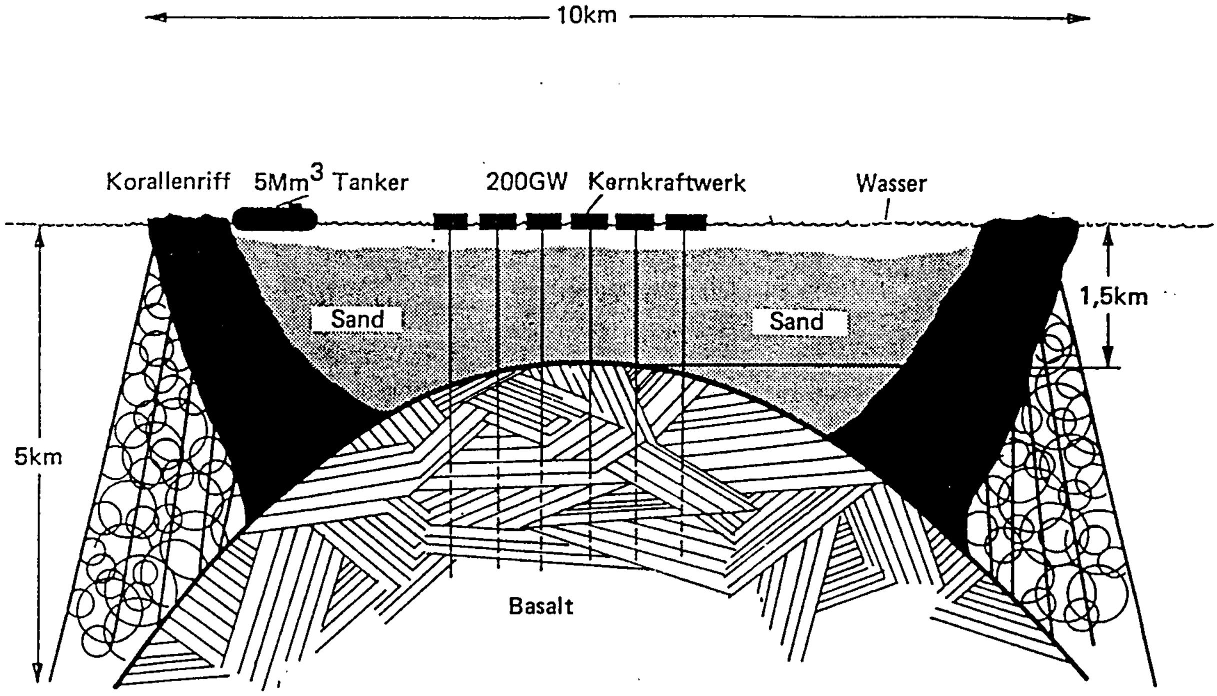
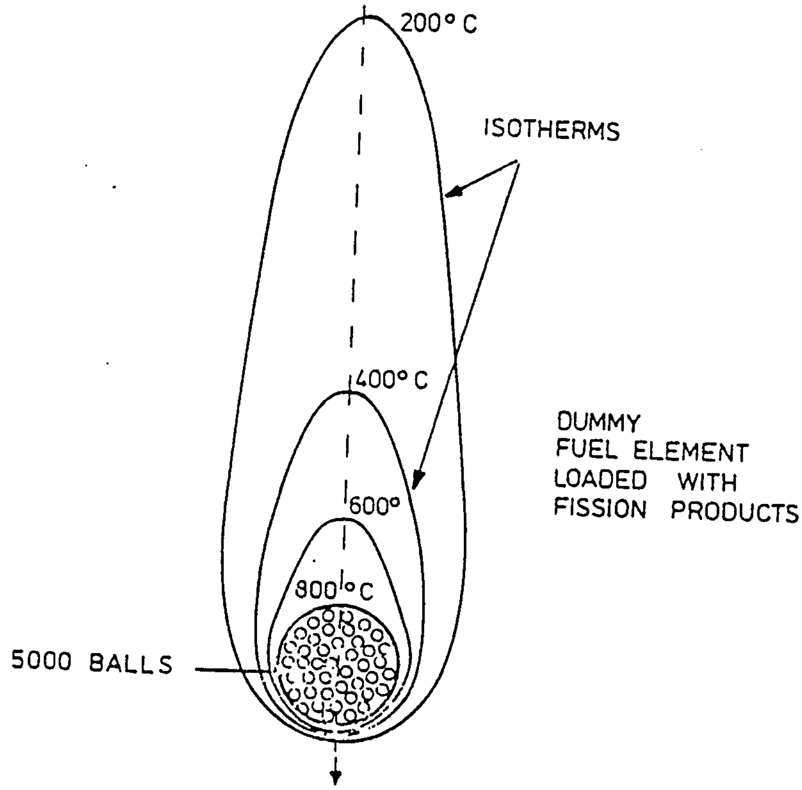


Figure 16.

As said in the text, the plant is composed of large reactors (e.g., 200 GWth) on barges, which are completely selfconsistent, providing fuel reprocessing and disposal into the basalt bedrock. These atolls sit usually on top of an exhausted volcano cone. The atoll taken as reference exists, and is called Canton Island. The heat from the reactors, presumably of an HTR type, is used to split water into H_2 and O_2. Following development after my original proposals in 1968, the Japanese are developing a thermochemical process to split water (UT-3), a HTR, and a system to extract uranium from sea water. The water is pumped from a certain depth (500 m, 5°C) to reject it at surface temperature (25°C) avoiding hot spots. The pumps operate on an OTEC principle, working even in case of a plant shut-down, so that the cold water would bring again into the depth any radioactive stuff released during the shut-down.



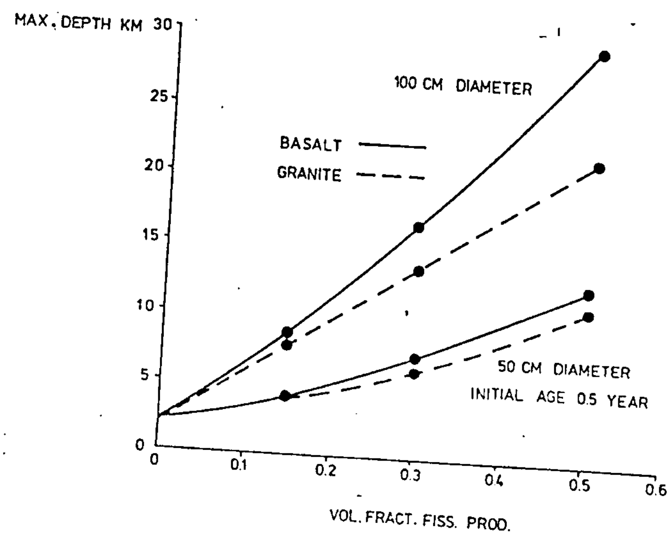


Figure 17.

Fission product disposal is obtained by using the low conductivity of earth and rocks. With sufficient (and feasible) fission product concentration and size, the rock melts and the cartridge sinks. In due time it can reach 20 km of depth or so. In the figure the critical mass for sinking is obtained by putting together a number of balls, at the bottom of a 1–2 km long injection pipe. Quite a number of experiments done in the 1960s with dummy sinkers show that the thermo equations can be trusted.