THE FUTURE OF HYDROGEN
An Analysis at World Level, With Special Look at Air Transport

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Abstract

Technologies are usually introduced at the market level when the context requires them. To forecast when hydrogen will be introduced as an energy vector, I analyzed the context of the level of the energy system, and at the level of the air transportation system. Both contexts indicate for hydrogen fuel a commercial introduction toward the end of the century. The main drive in the area of aviation is the bottleneck in the increase in jet engines' power that can be solved only by going hypersonic.

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Forecasting has become a really interesting trade since I accidentally discovered that the Volterra-Lotka equations of competition, originally developed for the biological realm, fit so well human affairs. After all, the most penetrating analysis of human virtues and frailties have often been done using images from the animal world.

What comes out from an extended diagnosis of economic, social and cultural processes is that the "system" is extraordinarily well organized and behaves with long term self-consistency. This means our will and initiative are certainly the necessary driving force to keep it ticking, but that the objectives and timing have better to be adapted to the system context if we are chasing for success.

The analysis of the dynamics of energy markets in physical terms, or the primary energy substitution at world level, is reported in Figure 1, fitted with the system of logistics solution of the Volterra equations. I have probably shown this figure a thousand times. Taking the equations in a predictive mode, it shows coal and oil as the loosers, gas the winner in the medium term and nuclear plus fusion in the long term.

The equations reported in Figure 1 give not only the trends but the precise time pattern of events to come, and in order to boost the confidence of the listeners, I usually show a forecasting-backcasting experiment (Figure 2) done into the past, so that we do not have to waste time waiting for the future to come to us.

The experiment consists in slicing twenty years of data out of a time series of about one hundred years, that of primary energy markets shown in Figure 1. The slice is that between 1900 and 1920. Using *only* these 20 years of data, we can fit a set of equations and project them forward and backward in time. Then we superpose actual statistical data and compare them with the projected equations (Figure 2). *Et voilà*. It might seem preposterous that in 1920 one could predict the market share of oil in 1980 with a precision of a few percent, but it is just like that. And I reinforce the dose by saying one could have also predicted the flare of oil prices at the beginning of the seventies and their ebb a dozen years later. I certainly predicted the ebb, if only in 1980.

Reexamining Figure 1, one sees the system moving progressively from wood to coal, to oil, to gas. This means toward fuels richer and richer in hydrogen. This is even more evident from the consumer side, were, e.g. oil products are all richer in hydrogen than oil itself. From a Darwinian point of view, it looks as if hydrogen competes with carbon inside the fuel system and moves to win.

The observation can be put to test by looking at the ratio H/C for the mix of fuels at any given time. These primary energies are very inhomogeneous stuff, but I took some sort of weighted means, 0.1 for wood, 1 for coal, 2 for oil and 4 for gas. The result is reported in Figure 3. Extraordinarily enough, the competition follows a logistic path, as it should in a 1:1 context. It should also give complete victory to the winner, but here the fuel richest in hydrogen, natural gas, has only a ratio of hydrogen to carbon of 4:1. Should victory stay at 80%? At this point we can make the hypothesis that the system keeps going as it likes, in its usual way, and we have to take care of its *desiderata* by providing extra hydrogen from an external source, obviously water.

Such simple hypothesis gives us the possibility to calculate the time when industrial water-splitting will start, using obviously nonfossil primary energies.

This means using hydro or nuclear. The next question is if the indications so constructed make sense in the general context. The dates, one can get from the figure, are late nineties for the world, and early nineties for the FRG, analyzed in the same way. They are not contradictory as the FRG is a small nick at the world level.

As the primary source cannot be fossil fuels, because they are already counted, we are left with hydro and nuclear as said already. Let us look now at the situation more in detail. Hydro, at world level, is still a fairly unexploited primary resource, even in a developed and capitalized country like Canada. The main reason for that is most probably that electricity is a stuff quite difficult and expensive to transport over thousands of kilometers. The thin power lines I can seen when I fly over northern Canada are sitting in no man's land, going from nowhere into nowhere, and make me shudder at the thought of the construction and maintenance problems.

Being airborne, I repeatedly estimated that a couple of planes concocted by joining the body of a Super Guppy (for volume) to a wing plus power plant of an Antonov 22 (for lift), could shove the LH_2 from a one Gigawatt (primary) electrolysis plant in Canada to a rocket site in the US. Even if the Gigawatts were 50, the scale and complication seem treatable, and, if the final product has to be LH_2, the scheme looks more aesthetic than a maze of power lines or a fleet of trucks. This small detour into aviation is also motivated from the fact that LH_2 has to learn to fly, as we will see in a moment. The sooner the better!

In the primary energy analysis of Figure 1, hydro does not even appear, being less than 1% of world level and finally nuclear energy will carry the thrust. The equation, against which it is presented in Figure 1, does not fit its actual penetration rate, but it shows how nuclear energy should behave if it would follow the rules of penetration of the fossil fuels. It penetrates actually much faster, and this is due to the fact that nuclear heat is sold to a preexisting system with a distribution network already in place. Coal, oil, and gas had to dig their own.

The electric grid is a mixed blessing for nuclear energy because it makes its life easy, except for the fact that its capacity will be soon saturated. A similar thing did happen to natural gas when it entered European countries, where city-gas distribution was already in place. Penetration had to kink to a slower pace when this niche filled up. In spite of all the efforts to make nuclear small and cozy, the only viable variety seems big and distant in this configuration. The only product alternative to electricity seems to be hydrogen.

Time is the necessary ingredient of strategy, so let us look at the situation in a time frame. For that I will use two concepts, one, we have already seen, an innovation, develops logistically to fill its *niche*. In multiple competition the situation is a little more complicated, but that is the message. The second concept is that our Western societies operate in a pulsed way, with a period of about 55 years. Most innovations start and saturate inside one of these time boxes. It can restart and saturate at a higher level during the following time box. Our box ends around 1995 (it started in 1940) and that is why all markets look saturated. And why recession is going to last until then. And why everybody runs exagitated in order to start something new.

So let us use our diagnostic eyeglasses to the case of nuclear energy (Figure 4) at world level. It saturates around 350 GW about 1995, as it should. These 350 GW are not bad as they represent about one Terawatt primary heat, or more than 10% of world primary energy consumption. The penetration is still more advanced in France, where about one-third of the primary energy will be available from nuclear in 1995. This means the electric network will be saturated, and if Framatome does not want to recess into a maintenance configuration, it has to fight its way into a new product, i.e. hydrogen. As our French colleagues here will tell you, there are many signs of moving into action there. Just for illustrative purposes, the case of France, Canada and Japan are reported in Figures 5, 6 and 7, for what concerns nuclear's penetration, expressed in Gigawatt electric installed. Primary thermal power is roughly three times as much.

If hydrogen from nonfossil primary energies is going to start penetrating soon, the next question is in what markets. Usually the markets penetrated first are the ones where the stuff is at a premium. Curiously enough both oil and electricity started their careers in the illumination business. My suspicion is that aviation has many reasons to be interested in hydrogen, and I will make an analysis of the whys. Because the *scheme of this analysis is of general character*, it can be applied to each other branch of business using energy to see when the times are ripe. Ammonia synthesis and fuels hydrogenation are areas of obvious interest.

Coming to the air transport system, its "product" is expressed in ton km/h or passenger km/h. Figure 8 shows the evolution of air transport from 1945 to present fitted with a logistic growth function. Just in passing I attract your attention to the fact that the dynamics of the growth did pass absolutely unscathed through two major increases in the price of jet fuel, in 1973 and in 1979. This powerful homeostasis of large systems is very useful to make forecasts a work of precision. About 95% of the saturation point of around 200 x 10^6 pass-km/h will be reached in the middle nineties. The figure also reports the dates when successful first level aircrafts were introduced.

Air traffic can be visualized as a flux, but also an airplane, where productivity can be expressed in ton km/h or pass-km/h. Because also this productivity grows logistically in time, it can be shown in a renormalized form together with traffic (Figure 9). In this figure also the pre-war tail is reported (1% of the saturation point!), basically to locate also the mythical DC-3. The very interesting point is that the traffic line (dashed) and the productivity line are almost parallel, meaning planes productivity is always a constant fraction of traffic. This finally translates into the fact that the number of planes is independent of traffic. IIATA members, the core of commercial air transport, always had about 4000 planes in spite traffic increased about 80 times since 1950. If we look forward to the next 10 years, we see that the Jumbo-1000 with thousand passengers and the usual Mach-0.8 speed will satisfy the increase in demand developing now. It is already designed, with three decks, although not yet certified. The "long humps" now selling are just its precursors. This plane may require engines with a thrust of around 30,000 kg. We can now construct a link between traffic demand and engine size. This will give the link to hydrogen.

The history of engines is reported in Figure 10. It splices into two logistics, one per Kondratief box, as usual for many technologies,. The problem for piston engines was not speed. After all, one can run a jet system using a piston engine as the Italians did in 1937. Their problem was power. The most sophisticated versions reached just above a couple of Megawatts. An engine is a thermodynamic machine, and its power depends on the mass of working fluid it can process. The intricate inlets and working spaces did limit the breathing capacity and the power of the piston engine. A jet engine is straight and can process all air its cross section can inhale.

As we see from Figure 10, the thrust of subsonic jets appears to saturate at about 28,000 kg, which very roughly corresponds to a cruise power of just above 20 MW. Saturation points to internal difficulties for the system just as in the case of the piston engine. The problem here is that the cross-section, which is the prerequisite for power, grows as the square of linear dimensions, but weight tends to grow as the cube. Aircraft operators like to have two engines, and not twenty, so engine manufacturers have to improve technologies to overcome the handicaps that come from size. As Figure 10 shows, they managed very well but they now seem to be out of breath.

Because the flux of air depends not only on the cross-section but also on speed, it is this variable one could tackle for the next jump. The same engine size at Mach-8 can provide ten times more power than at Mach-0.8. Rule of thumb, naturally. On the other side the airplane, flying at Mach-8 will also have its productivity increased by a factor of ten. So we may have the potential to increase air traffic by an order of magnitude, with airplanes carrying no more than 1000 passengers which has the scale of a train. It looks also that the hypersonic plane, so forcefully predicted by President Reagan, will be a necessary piece of furniture in our near future.

There is no need to make an effort in guessing what kind of fuel these planes will use. All maquettes manufacturers wave in the twilight, are suspiciously fat. What I will try to assess is the when and how large may be their fuel demand. As indicated in Figure 9, the Jumbo-1000 will be in demand in 1990 and will remain the work horse of the air transport well to the end of the century.

Following the rules, the next logistic wave will formally start in 1995, like the last one in 1940, and we have all reasons to expect a substantial growth in passenger kilometer. A hint in that direction is given in Figure 11, where pass-km for the main intercity transport systems for the US are reported. Train and bus are out, and the competition is now between car and plane, the latter winning with a cross over before 2010. Because the time constant of this substitution is about a Kondra cycle, as usual, it will go from 10% of 90% of the pass-km before the end of the next cycle. Air traffic will then increase by an order of magnitude even without taking into account the evolution of total traffic. It is in fact well known from the Zahavi model on travel demand, that people travel consistently about one hour per day, and consequently their mileage increases when more time is allocated on faster transport media, like the airplane versus the car. On top of that for such relatively long time periods one should also account population increase.

What did happen during the present Kondra, was an increase in pass-km by *two* orders of magnitude. Analogies with successful technologies spanning two or more Kondra, e.g. steel production (Figure 12), a factor of ten increase in air transport can be considered conservative.

The fuel demand of such a system can be estimated on the basis of general considerations. What happens in fact is that fuel consumption per pass-km appears fairly insensitive to transport mode. Technological progress seems in fact a way to get more speed almost for free. Let us say aircraft engineers will have to make miracles in order to keep that true. Incidentally, the physics of hypersonic flight says that this is in principle possible. Because present aviation (extrapolated to 1995) consumes about 100 GW of fuel, ***the next round of planes will consume about 1000 GW***. It will be inevitably LH_2 and the estimate is conservative.

One can object that most short- to medium-range traffic will still be done by subsonic planes. True. But one should not forget that the first level planes are the workhorses. Today the 747 carry about 75% of all the world traffic expressed in passenger or ton kilometer.

The next question is when. Past experience for introducing new successful models can be enlightening. As shown in Figure 13, the "flux" of a plane is matched to the world traffic "flux". But air frame makers have also to match their manufacturing capacity to the demand pulse when it materializes. For that they have to start manufacturing with a certain anticipation in order to build up and streamline their capacity. An analysis of two extremely successful aircrafts, the 727 and the 747, shows an identical pattern and an anticipation of about 9 years (Figure 13 shows the case for the 727).

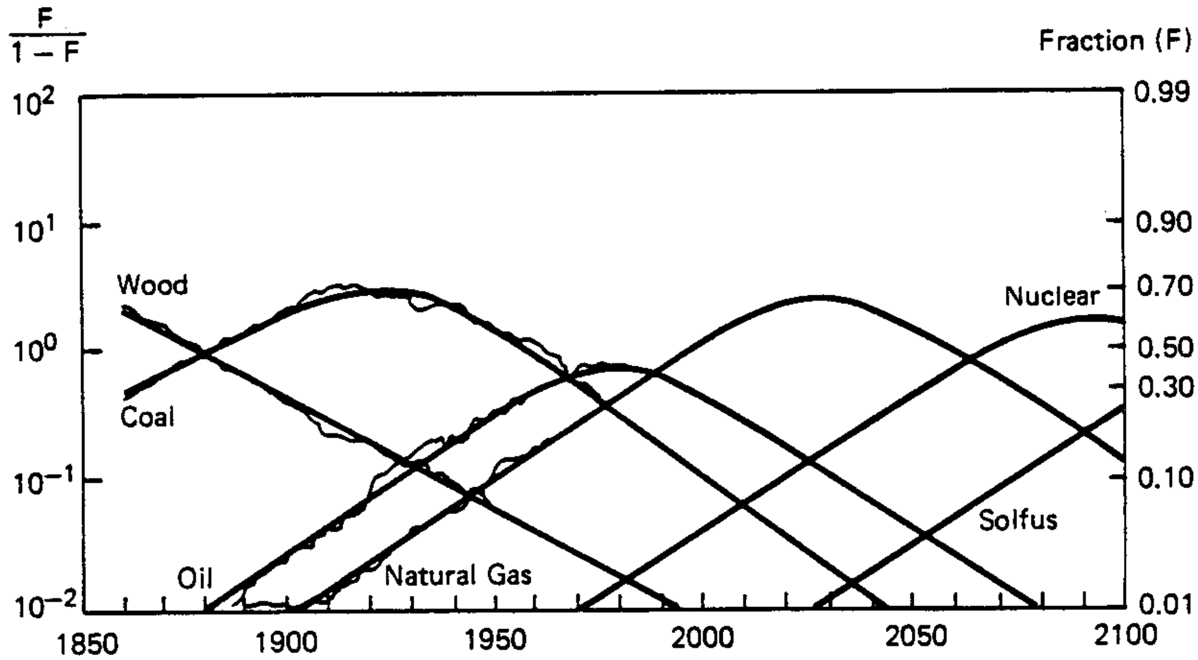
The timing of the first commercial version of a supersonic-to-hypersonic plane would be then around the end of the century, which by the way is only 14 years from now. Such a period of time is well matched to a determined effort in

R&D to fly such airplanes. It is obvious that the United States is the only place where this can occur, and as the presidential message indicates, where this may occur. As de Gaulle once said, "*l'intendance suivra*". We are *l'intendance*.

Figure 1

Primary energy market share dynamics using the logistic function system solution of Volterra-Lotka equations to fit the statistics.

Figure 1



World primary energy substitution. Source: N. Nakicenovic (IIASA).

Figure 2

An experiment in forecasting. Twenty years (1900-1920) of primary energy market share are taken as data base (Figure 2a). A set of logistic equations is fitted to the data and extended outside the data base (Figure 2b). The extended equations are compared with actual data (Figure 2c). The case of oil shares is particularly striking as the share in 1980 could have been predicted in 1920 with a precision of a few percent.

Figure 2

World—Primary Energy Substitution (Short Data)

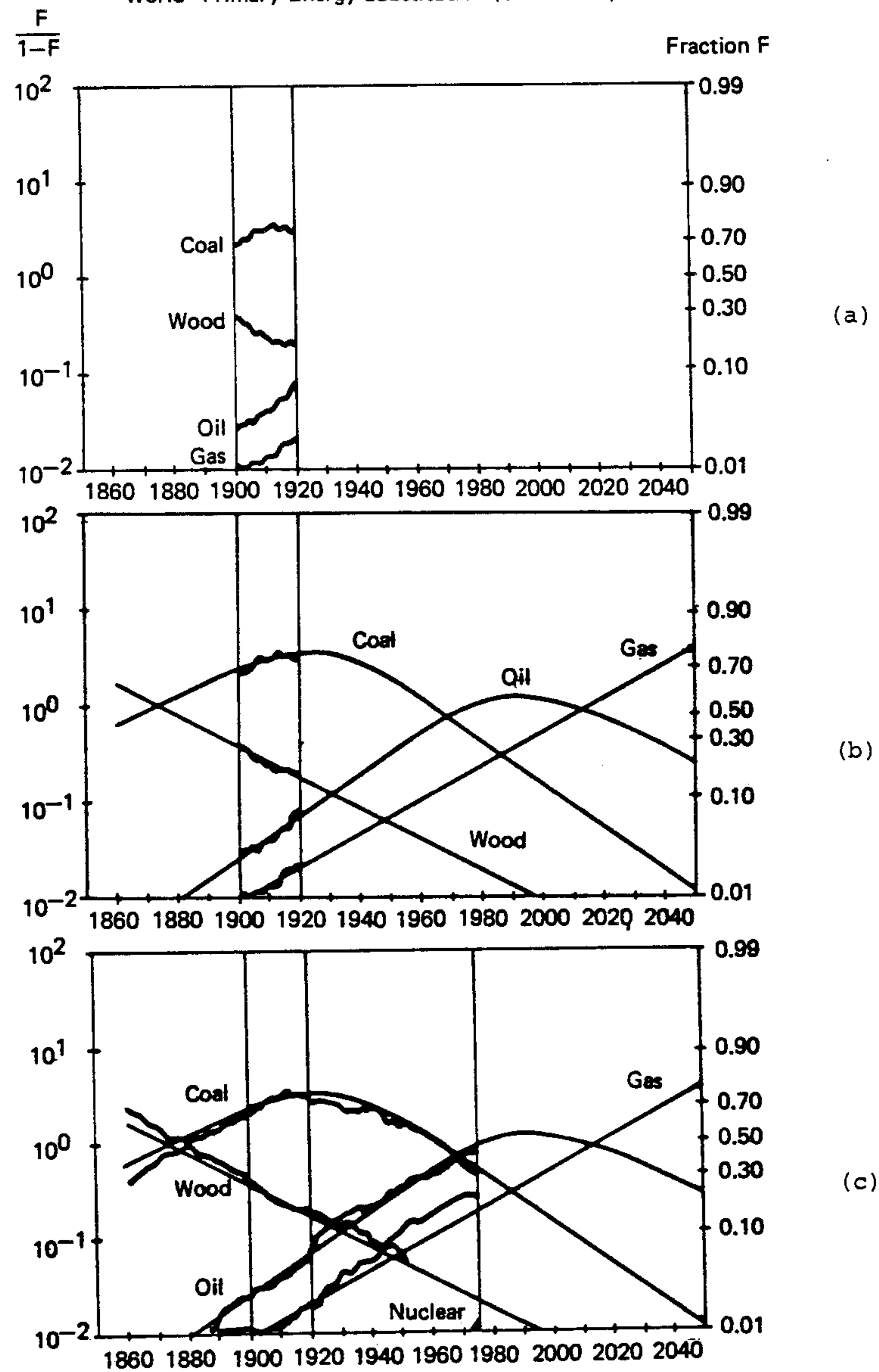


Figure 3

The ratio of H/C is reported from 1860 for the mix of fuels for the corresponding years. Hydrogen and carbon behave *as if* they where competing for the energy market, revealing a secular dynamics in the techniques of energy use. One can infer these technologies imply a larger share of hydrogen the fossil fuel system can provide, when the extrapolated H/C curve starts deviating from the data. The special case of air transport technologies is treated in the text.

Figure 3

EVOLUTION OF H/C IN WORLD'S FUEL MIX

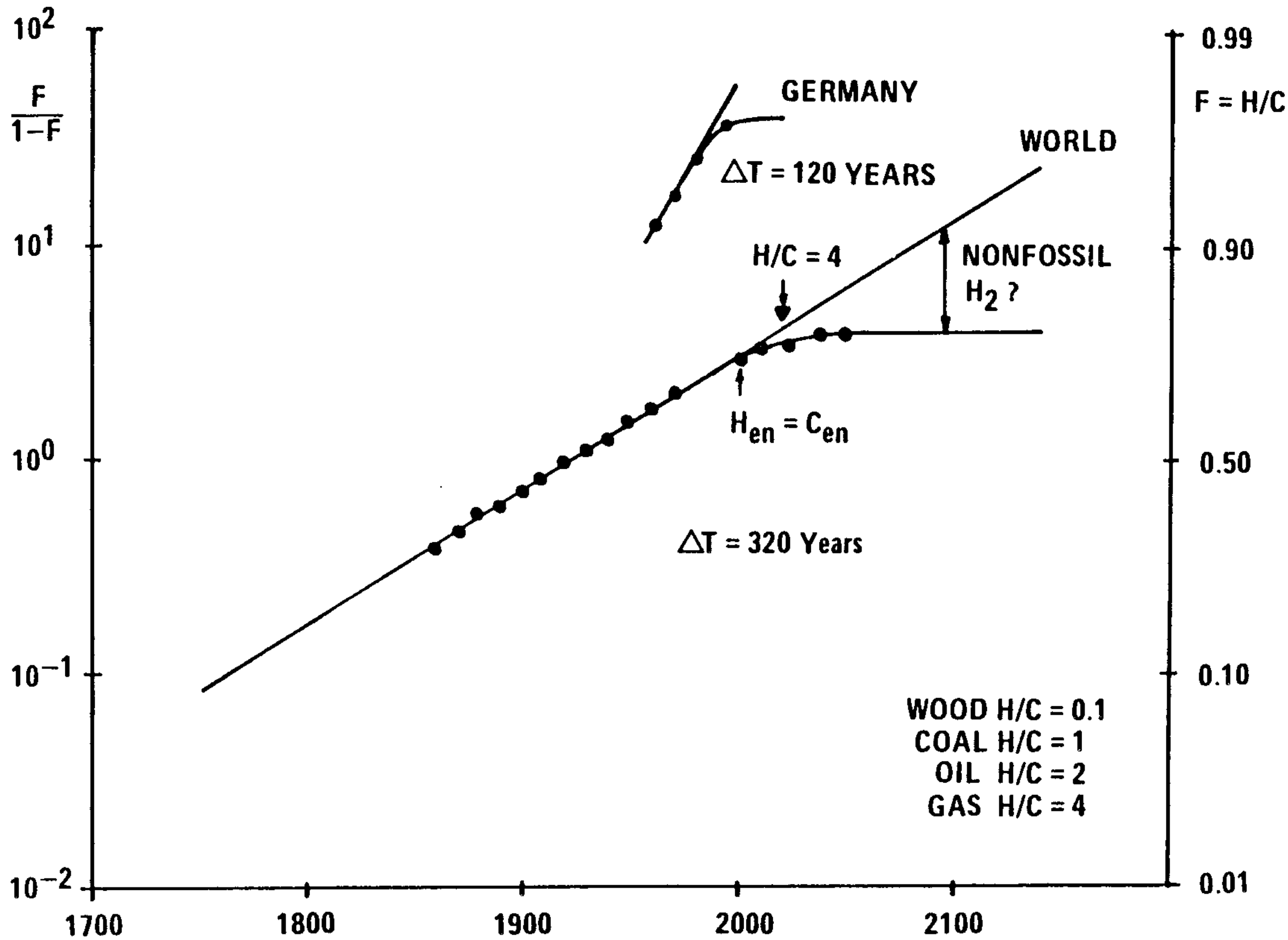
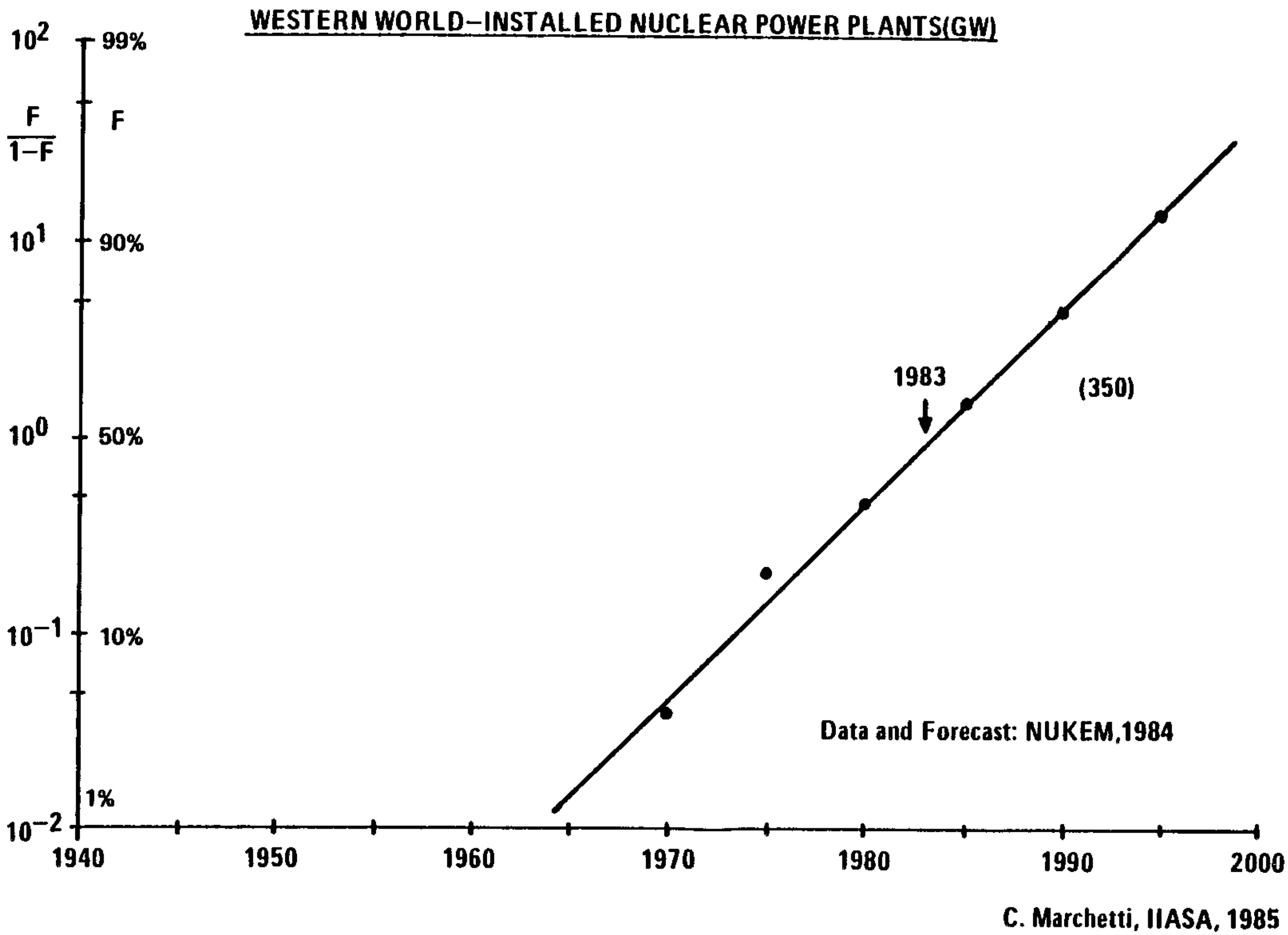


Figure 4

Nuclear energy has been the subject of immense debate, and it might be consoling to observe it was mostly hot air. The penetration curve (Gigawatts!) show a business as usual trend as for any other technology. Saturation around 1995 just shows the end of a Kondratief cycle. Fresh penetration curves will start from there, and their saturation points will depend on the way the nuclear-hydrogen industry will create appropriate packages.

Figure 4

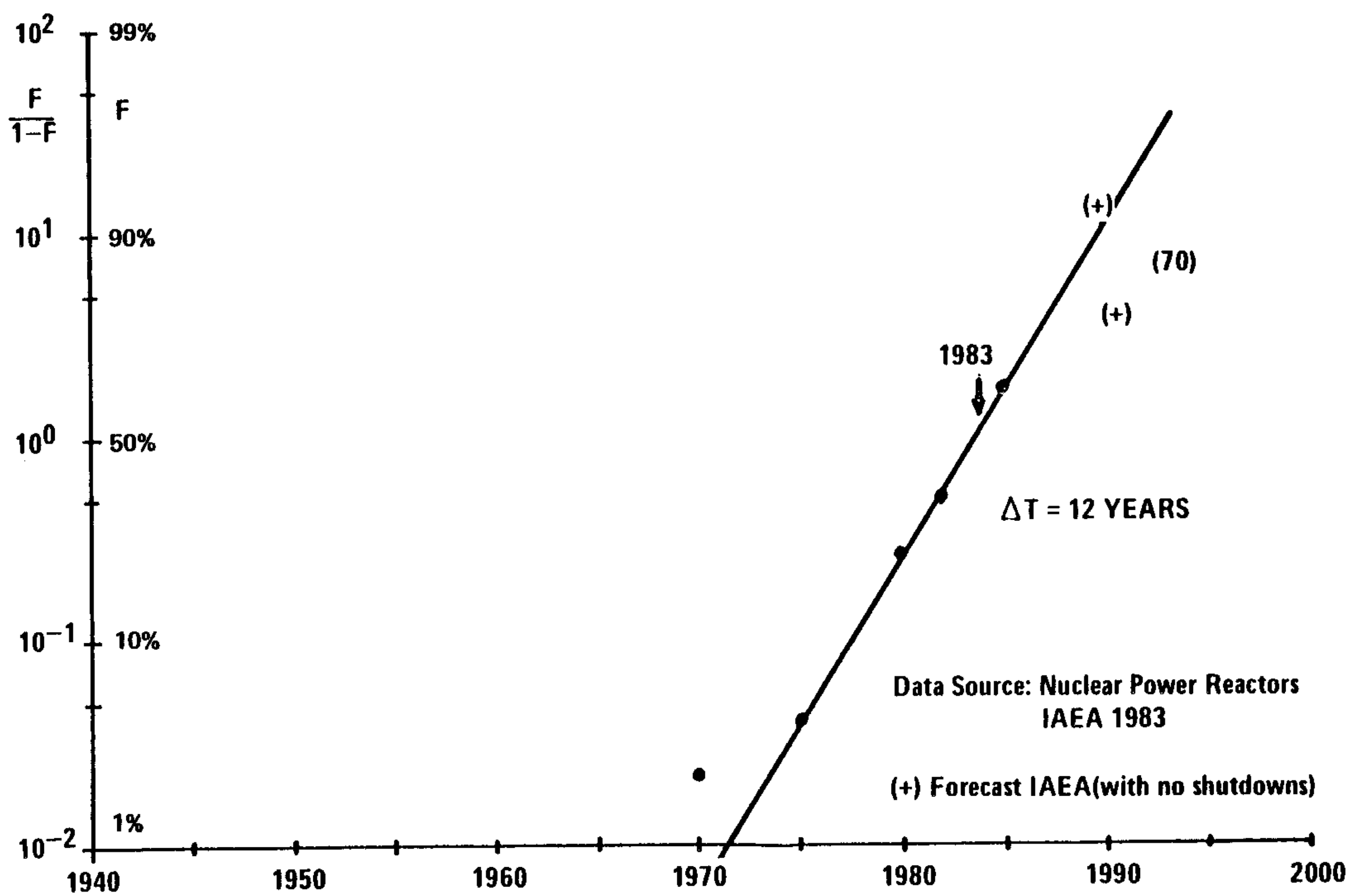

WESTERN WORLD–INSTALLED NUCLEAR POWER PLANTS(GW)
10^2
F/1–F
10^1
10^0
10^-1
10^-2
99%
F
90%
50%
10%
1%
1940
1950
1960
1970
1980
1990
2000
1983
(350)
Data and Forecast: NUKEM,1984
C. Marchetti, IIASA, 1985

Figures 5, 6, and 7

One could melt the three into a single picture. Nuclear energy has grown in a quite inhomogeneous way in various parts of the world, as the Gigawatts of saturation show. Countries more penetrated will have to start soon developing the nuclear-hydrogen package, at least to give a chance of survival and growth to their nuclear industry.

Figure 5

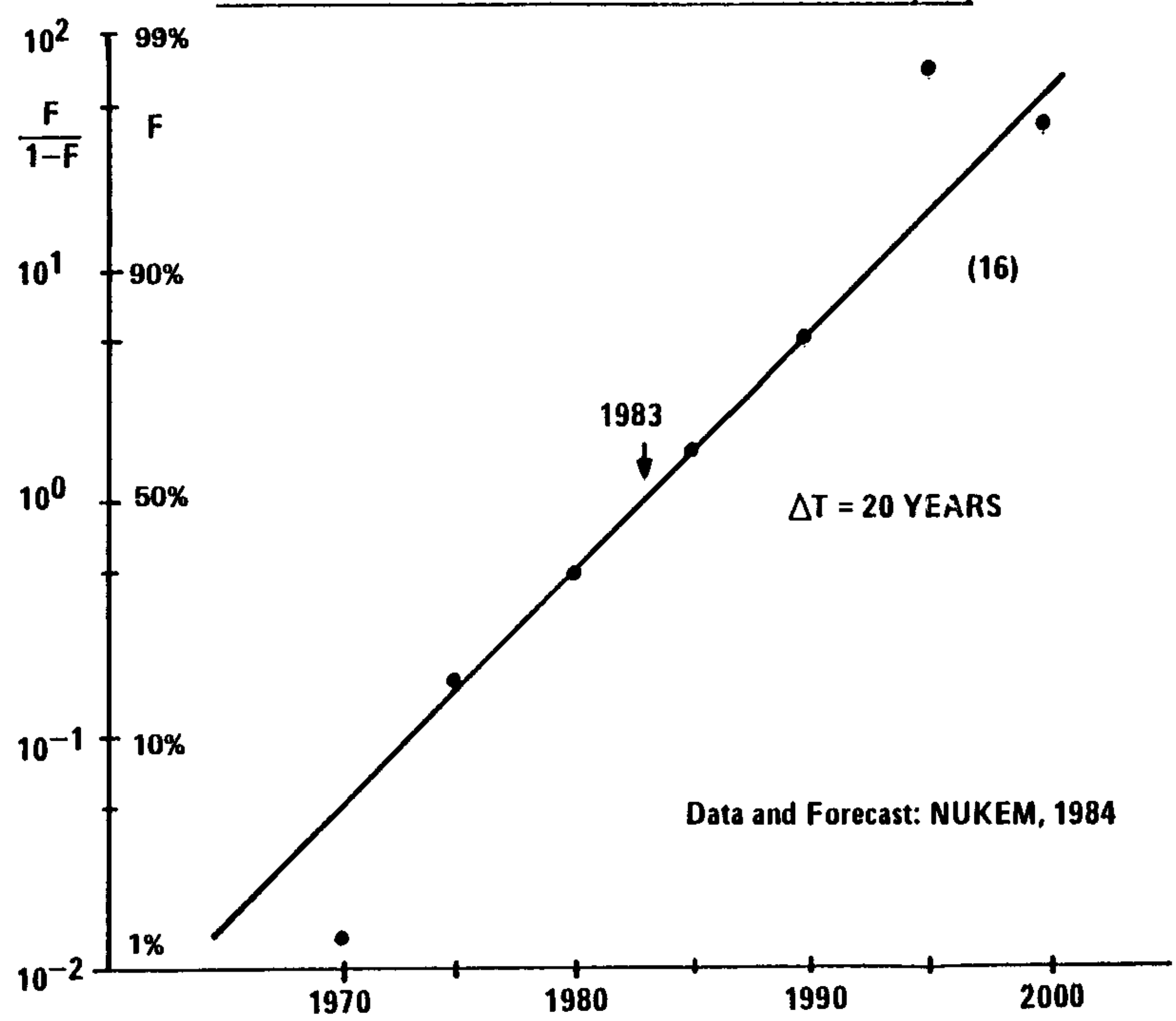
FRANCE–NUCLEAR POWER PLANTS (GW) CONNECTED TO GRID



C. Marchetti, IIASA, 1985

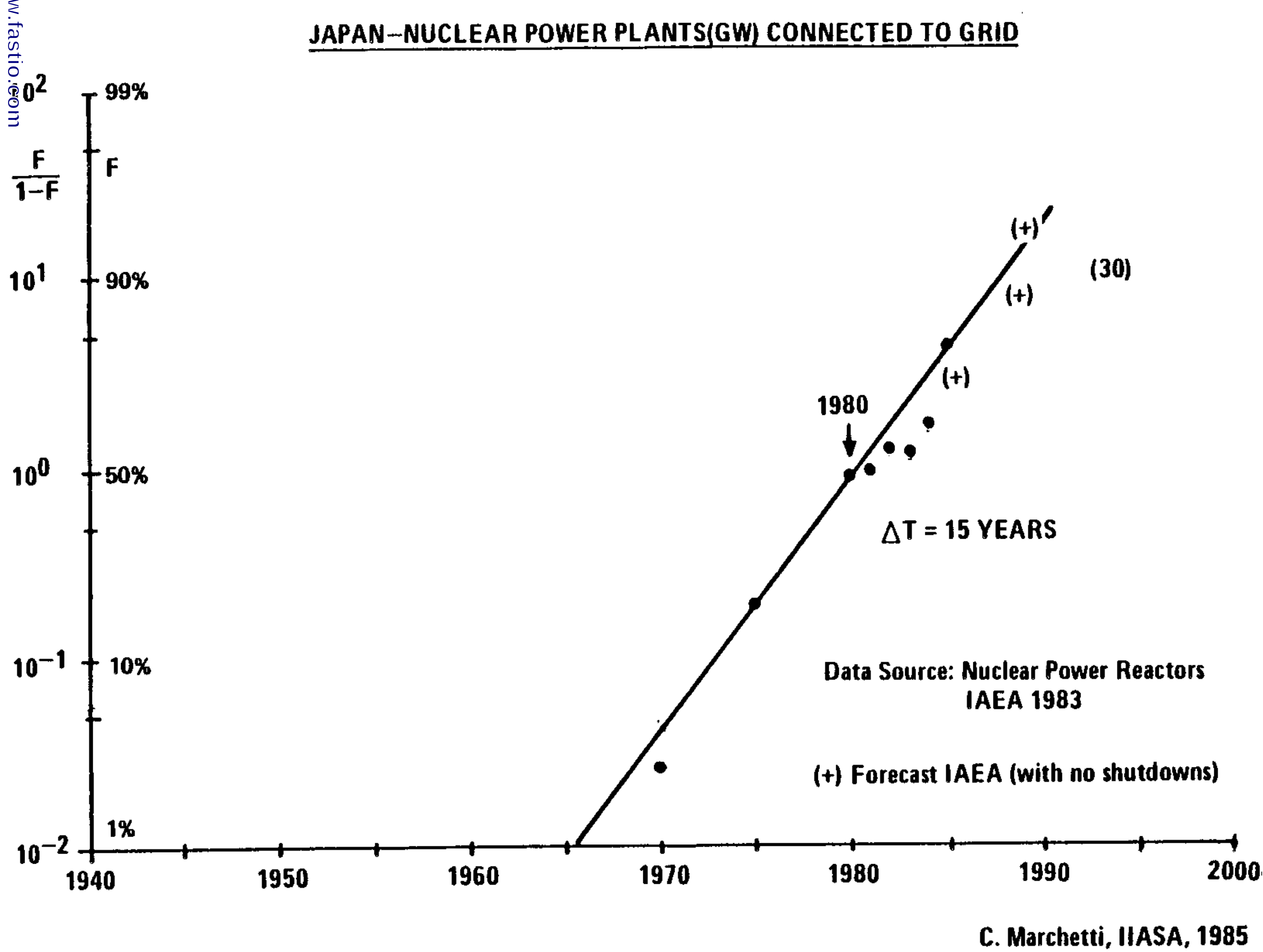
Figure 6

CANADA–INSTALLED NUCLEAR POWER PLANTS(GW)



C. Marchetti, IIASA, 1985

Figure 7



JAPAN–NUCLEAR POWER PLANTS(GW) CONNECTED TO GRID
10^2
$\frac{F}{1-F}$
10^1
10^0
10^{-1}
10^{-2}
99%
F
90%
50%
10%
1%
1940
1950
1960
1970
1980
1990
2000
(+)
(30)
(+)
(+)
1980
ΔT = 15 YEARS
Data Source: Nuclear Power Reactors
IAEA 1983
(+) Forecast IAEA (with no shutdowns)
C. Marchetti, IIASA, 1985

Figure 8a

Passenger-km/h transported by world airways. Also this service saturates around 1995-2000, following the usual Kondratief rules.

Figure 8b

Ton-km/yr transported by world airways. It is interesting to note that air traffic was absolutely unaffected by the large change in oil and jet fuel prices in 1974 and 1979.

Figure 8a

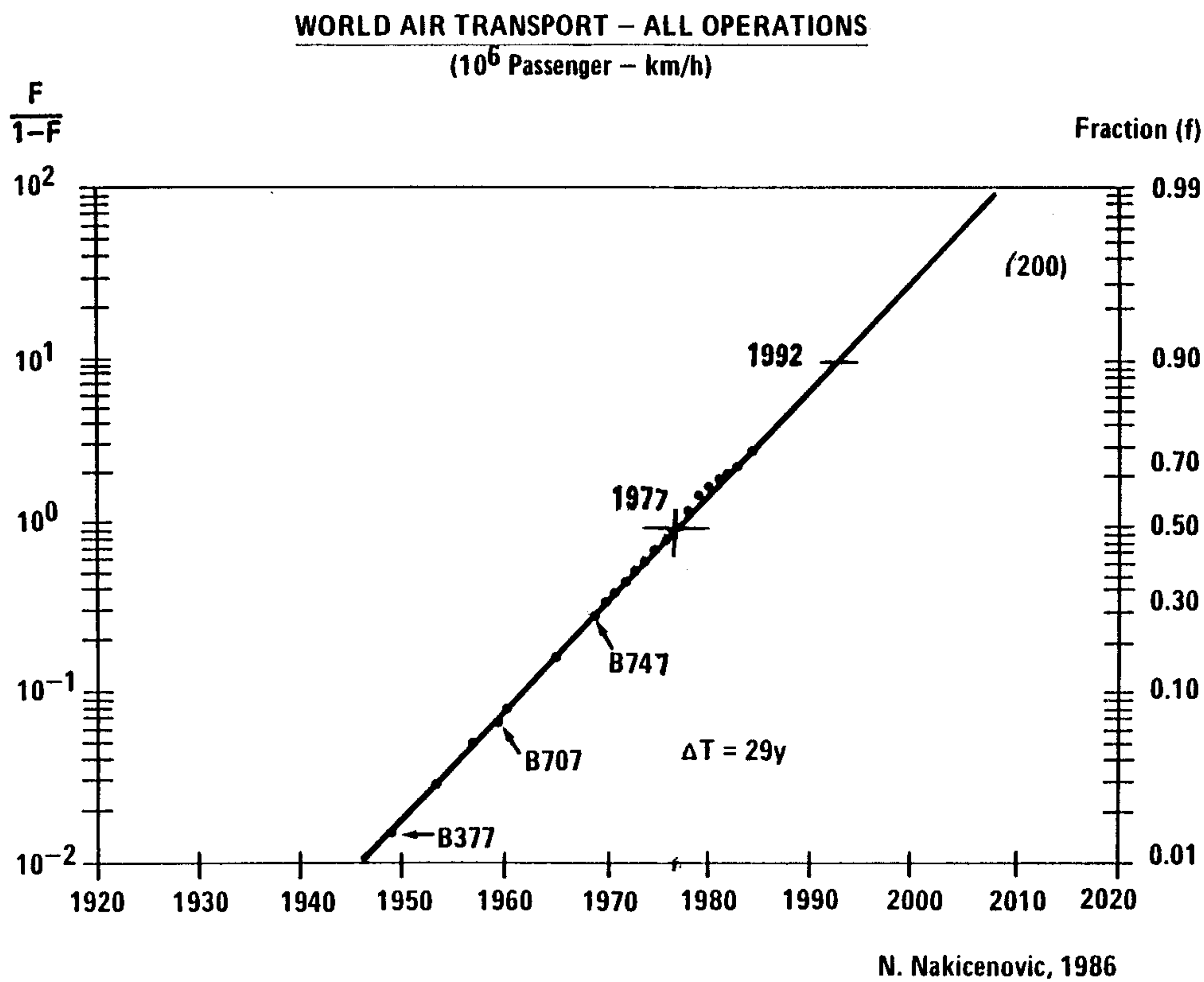

WORLD AIR TRANSPORT – ALL OPERATIONS
(10^6 Passenger – km/h)
F/(1–F)
Fraction (f)
10^2
10^1
10^0
10^–1
10^–2
0.99
0.90
0.70
0.50
0.30
0.10
0.01
(200)
1992
1977
B747
B707
B377
ΔT = 29y
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020
N. Nakicenovic, 1986

Figure 8b

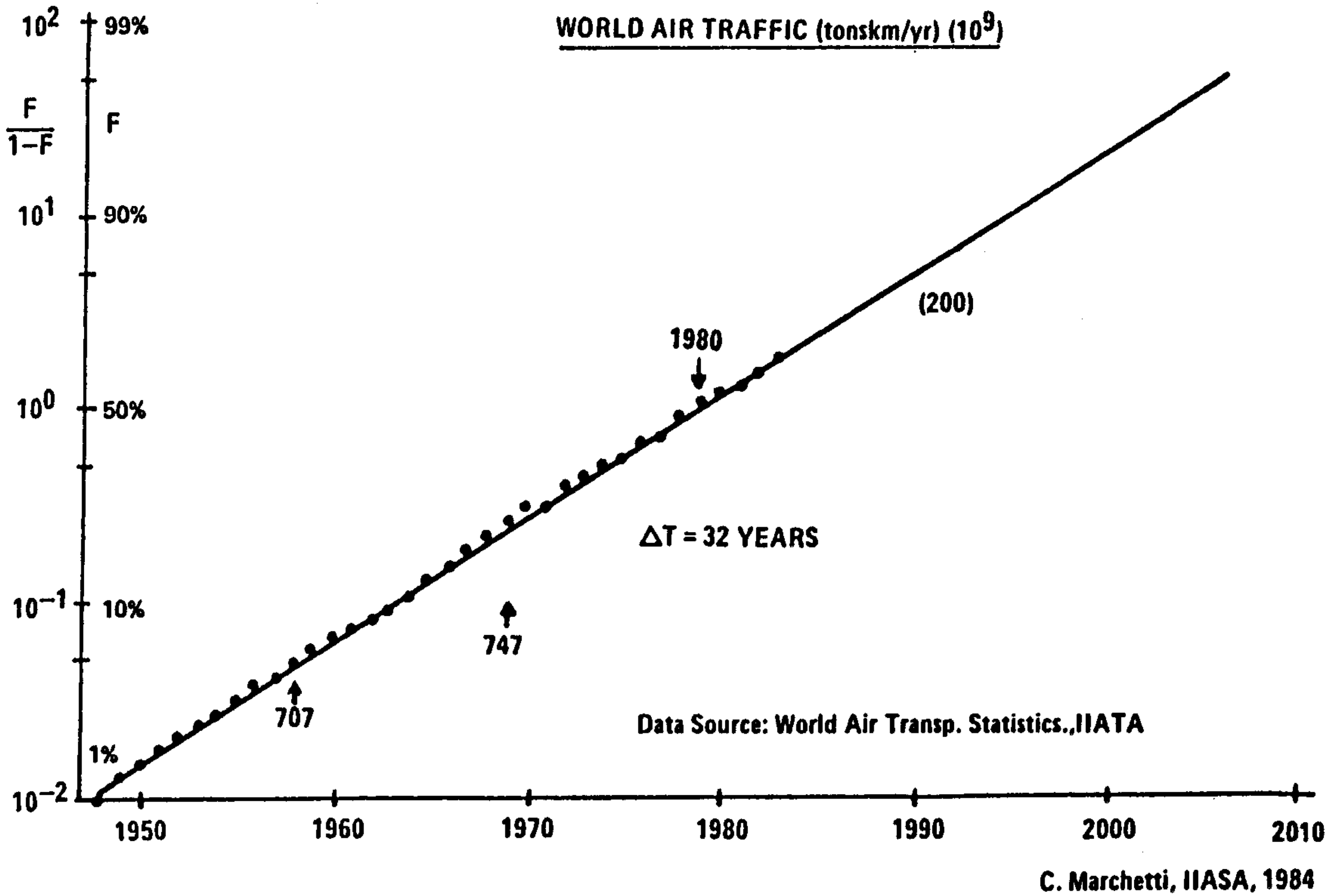

WORLD AIR TRAFFIC (tonskm/yr) (10^9)
10^2
10^1
10^0
10^-1
10^-2
F/(1-F)
F
99%
90%
50%
10%
1%
1950
1960
1970
1980
1990
2000
2010
(200)
1980
ΔT = 32 YEARS
747
707
Data Source: World Air Transp. Statistics.,IIATA
C. Marchetti, IIASA, 1984

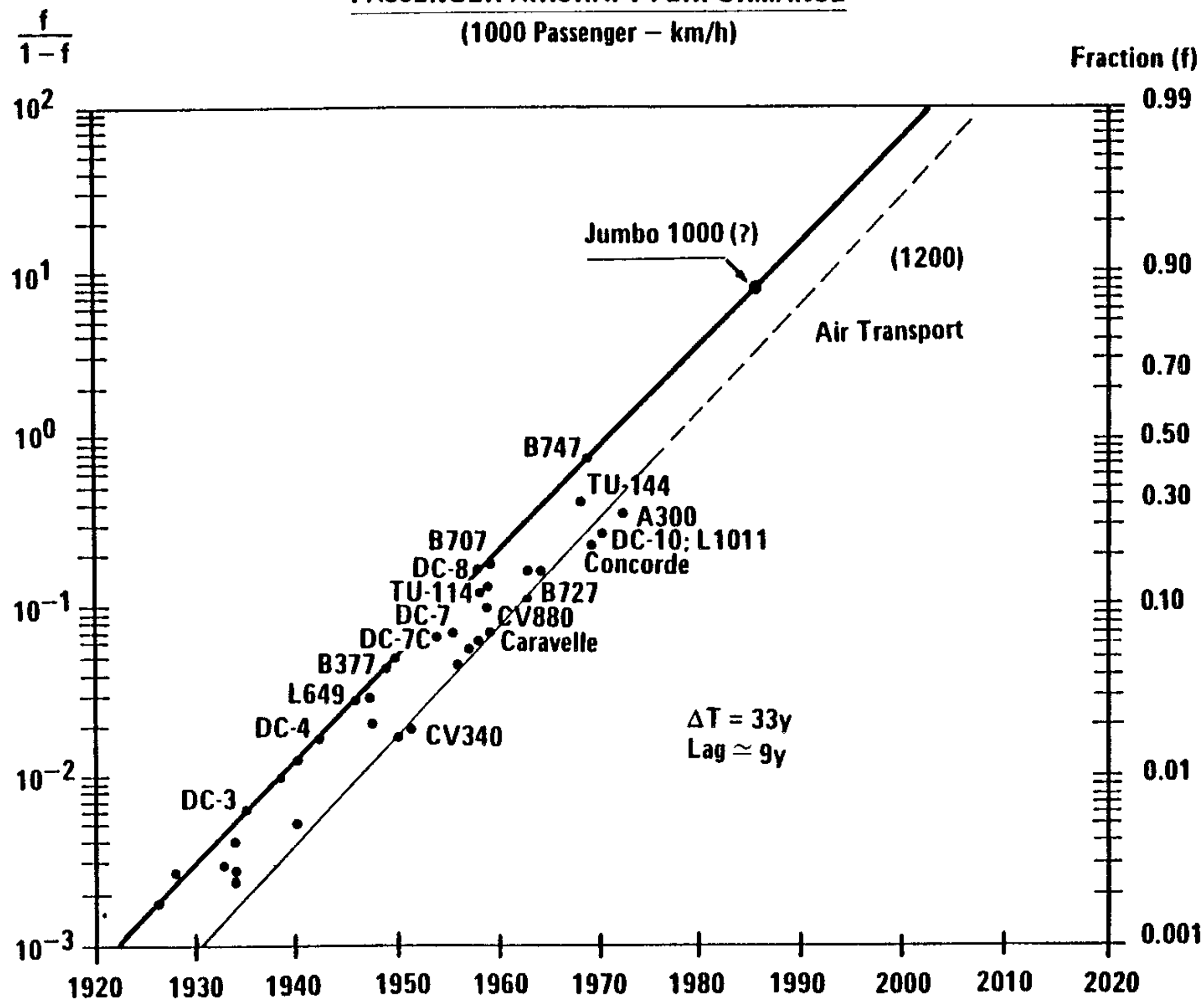
Figure 9

Passenger-km/h transported by an airplane is the measure of its productivity. The world traffic of Figure 8a is reported on the same scale as a dashed line. The fact the two lines are almost parallel means airplanes' productivity is always proportional to traffic. A consequence of that is that the number of commercial planes remains basically constant in time. An approximate date for the start of the Jumbo-1000 is indicated.

Figure 9

PASSENGER AIRCRAFT PERFORMANCE

(1000 Passenger – km/h)



N. Nakicenovic, 1986

Figure 10

Larger planes, as demanded by increasing traffic (Figure 9) require more powerful engines. Piston engines seem to have gone out of breath at the beginning of the fifties. Jet engines seem to be in a similar position now. The analysis points to a new technology necessary, which we individuate in super and hypersonic airplanes and engines. These engines are very likely to use LH_2 as fuel.

Figure 10

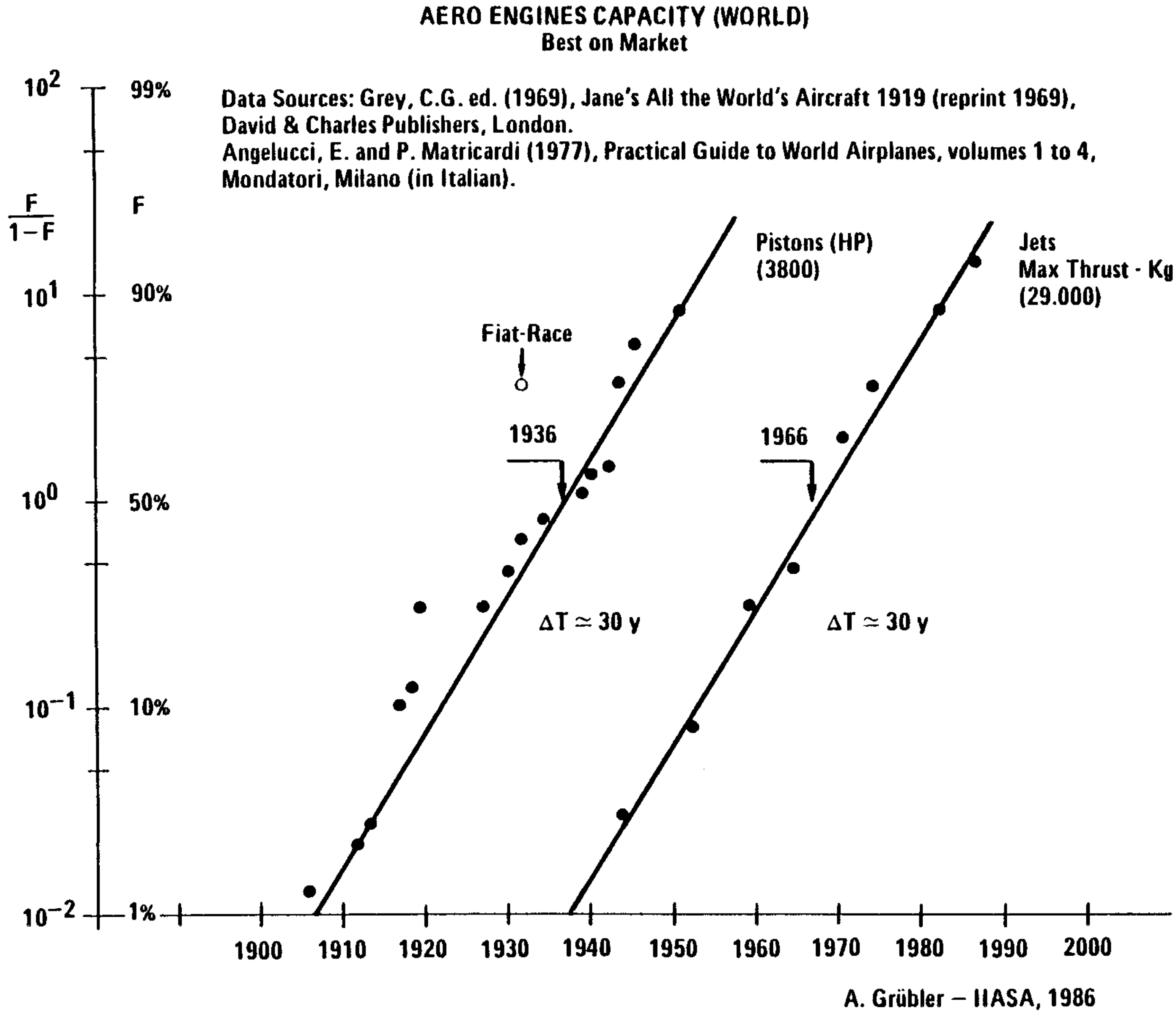
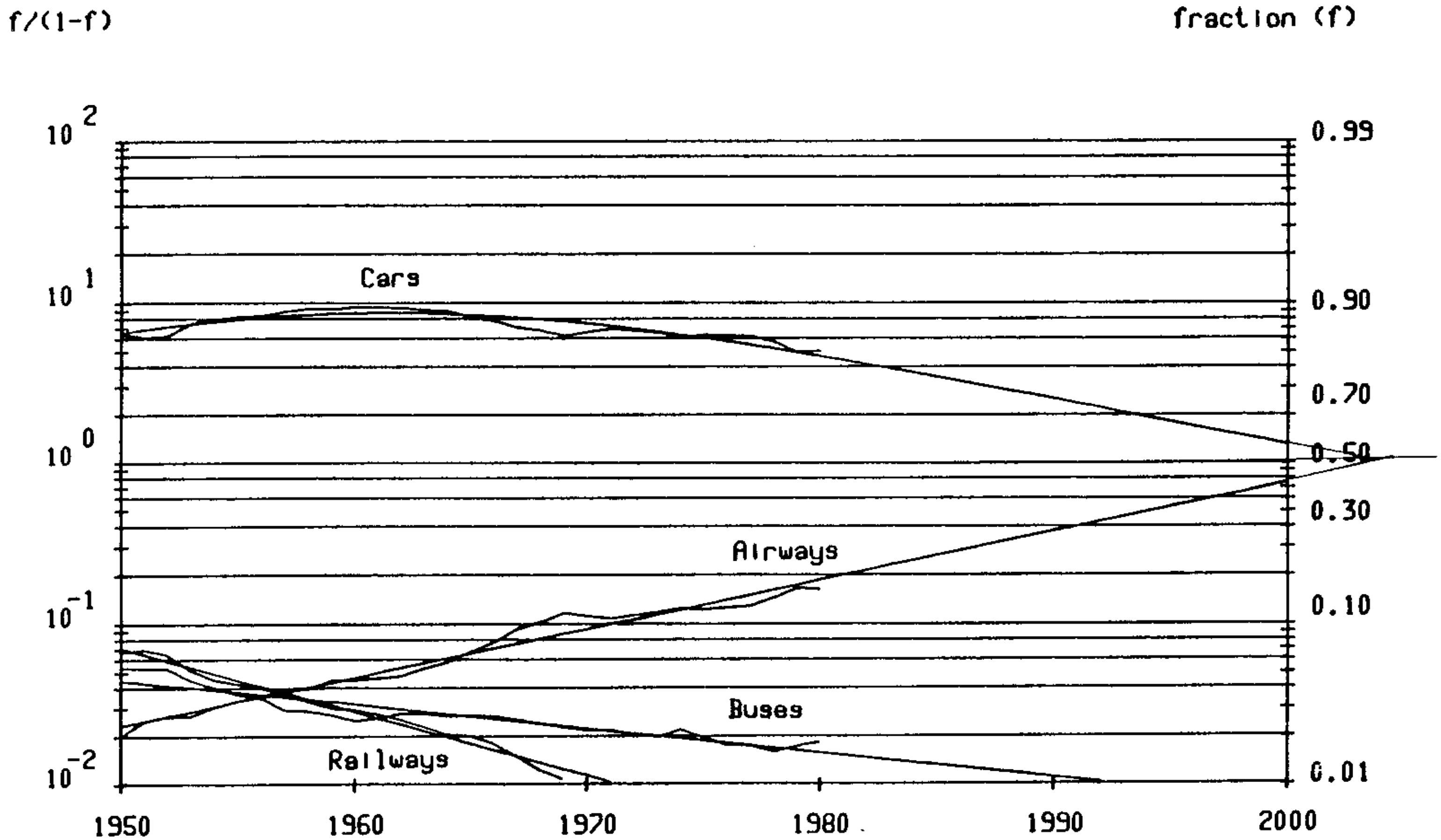

AERO ENGINES CAPACITY (WORLD)
Best on Market
Data Sources: Grey, C.G. ed. (1969), Jane's All the World's Aircraft 1919 (reprint 1969), David & Charles Publishers, London.
Angelucci, E. and P. Matricardi (1977), Practical Guide to World Airplanes, volumes 1 to 4, Mondatori, Milano (in Italian).
F/1-F
F
10^2
10^1
10^0
10^{-1}
10^{-2}
99%
90%
50%
10%
1%
Fiat-Race
1936
1966
Pistons (HP)
(3800)
Jets
Max Thrust - Kg
(29.000)
ΔT ≃ 30 y
ΔT ≃ 30 y
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
A. Grübler – IIASA, 1986

Figure 11

The competition between intercity modes of personal transportation in the U.S. is analyzed here for the last 30 years. The airplane appears the final winner, with an increase to its market share up to 90% during the next Kondratief cycle. The analysis indicates a possible increase of air transportation at the world level by at least an order of magnitude.

Figure 11

USA - Intercity Passenger Traffic Substitution



N. Nakicenovic, IIASA, 1986

Figure 12

The case of the expansion of a successful industry is here reported for the last two Kondratief cycles. Expansion was logistic, and the saturation point for the second wave has been just an order of magnitude higher than for the first one.

Figure 12

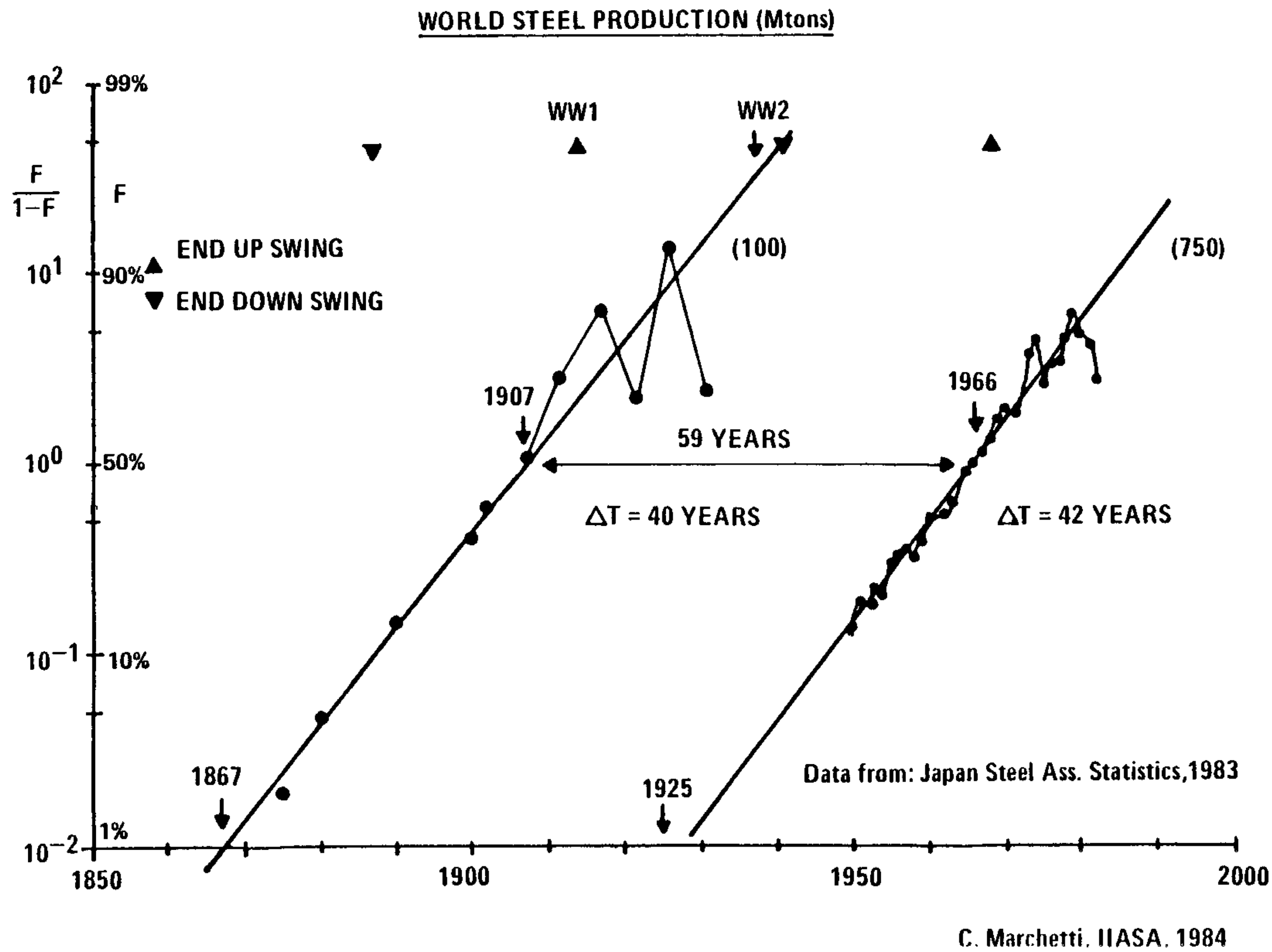
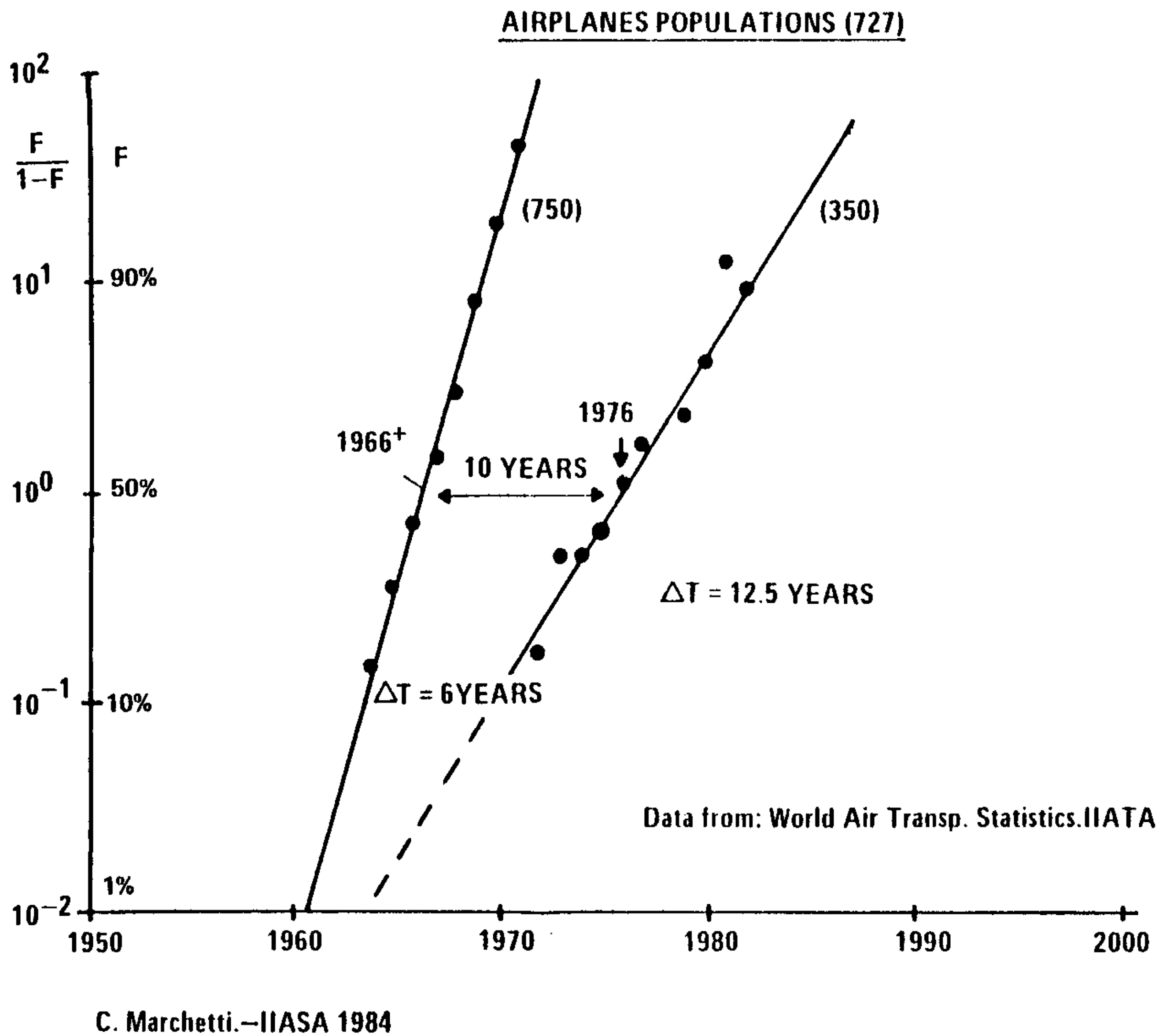

WORLD STEEL PRODUCTION (Mtons)
10^2
10^1
10^0
10^{-1}
10^{-2}
$\frac{F}{1-F}$
F
99%
90%
50%
10%
1%
END UP SWING
END DOWN SWING
WW1
WW2
(100)
(750)
1907
1966
59 YEARS
ΔT = 40 YEARS
ΔT = 42 YEARS
1867
1925
Data from: Japan Steel Ass. Statistics,1983
1850
1900
1950
2000
C. Marchetti, IIASA, 1984

Figure 13

Successful airplanes seem to follow a fixed strategy of market penetration, which permits calculating their commercial appearance from the time when they are needed, we can calculate from traffic expansion.

Figure 13


AIRPLANES POPULATIONS (727)
10^2
F/(1−F)
F
10^1
90%
10^0
50%
10^{-1}
10%
10^{-2}
1%
(750)
(350)
1966+
1976
10 YEARS
ΔT = 6YEARS
ΔT = 12.5 YEARS
Data from: World Air Transp. Statistics.IIATA
1950
1960
1970
1980
1990
2000
C. Marchetti.—IIASA 1984