A Forecasting Model for Research and Innovation Activities in Selected Areas: A Support for Strategic Choices [1]

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The primary objective of science is the construction of working models of the external world. The touchstone of the quality of a model is its ability to forecast. In a sense also science belongs to the "external world" as an object sitting there. The curious thing is that science never really developed a self-model able to pass the test of the forecasting ability touchstone. The point is that scientific activity is classified as a social activity, whose modelers are philosophers and social "scientists" who are very good at maneouvering words but very mean when quantities come into play.

Our work at IIASA during the last twenty years or so has opened up a new highway to bring the techniques of the hard sciences into the soft area of social behavior of which scientific behavior is part. The line of

[1] Presented at the International Course on Research and Innovation Management, organized by UNIDO and ICS, Venice, 13 September 1991

thought we adopted is very simple and I will formulate it *a posteriori*. Originally, in fact, we stumbled into it without clearly recognizing its internal logic. Very simply said: *Human actions are the consequence of the "epidemic" diffusion of "action paradigms"* generated somewhere into the depths of the social system, selected and sent into the wilderness in Darwinian fashion, to prove their worth.

The second observation that comes from the actual analysis of thousands of cases is that *societal action is of (quasi)fractal nature* in the sense that the above rule is valid independent of the hierarchical level of the actions. In other words, searching, invention, developing, enterprising, selling, are all run by the same mechanisms and *by the same mathematics*: the mathematics of epidemic diffusion at the various hierarchical levels.

Let us now look at the simplest diffusion process, that of a real epidemics. If we call $\overline{N}$ the number of individuals in a population which is *infectable* and N the number of individuals which have already been infected, we can write the equation for the new entries in the infected area in the form

$$dN = aN(\overline{N} - N)dt \tag{1}$$

which says that these new entries (in time dt) are proportional (a) to the product of the infected individual (N) spreading the epidemic and the susceptible individuals still around ($\overline{N} - N$). The solution of the equation is

$$N(t) = \frac{\overline{N}}{1 + \exp[-(at + b)]} \tag{2}$$

where b is the integration constant. Calling $F = N/\overline{N}$ we can rewrite equation (2) in the form

$$\log(F/1-F) = at + b \tag{3}$$

and we will show our charts mostly in that form (Fisher-Pry transform).

I will end here my little mathematics as we do not need much more to enter into the modeling of science and technology. For digging deeper, and studying e.g. multiple diffusion, which is run by Volterra equations, there is a list of papers reported in the bibliography.

Equations (1), (2), and (3) are reported in Figs.1, 2, and 3, drawn free-hand, in order to give a visual perception of their form. Fig.2 is the well known S-curve, the logistic. In Fig.3 the S is straightened by the Fisher-Pry transform represented by, e.g., equation (3). t_0 is the time of maximum rate for the diffusion. To give the rate (a) of the process in an intuitive form we express it in terms of the time (ΔT) the plague takes to go from 10% of $\overline{N}$ to 90% of $\overline{N}$. These two points are marked in Figs.1 to 3 with crosses. The relation between ΔT and a is the following:

$$\Delta T = 4.39a^{-1} \tag{4}$$

In the charts using the Fisher-Pry transform *the value of* $\overline{N}$ is usually reported as a *number in parenthesis*, and t_0 is given as a date.

As they say in Britain, the *test of the porridge is in eating it.* Let us see what happens with a real plague (Fig.4). We introduce here the problem of the appropriate indicators and that of the credibility of the data, two points of extreme importance for the applicability of the technique (as usual in the hard science). The credibility of the data comes first, and for that reason we adopted the number of deaths instead of the number of people falling sick, as it should be, as an indicator of the spreading of the plague. It contains the hypothesis that deaths are a constant proportion of infections, and, *a posteriori*, the proxy seems to work.

Coming to a subject nearer to our scientific interests, let us look now at the epidemic diffusion of research interest for a now popular subject of the *effect of* CO_2 *on climate*. The proxy in this case is the number of papers published (as selected by ISI, the International Scientific Index). The result of the analysis is reported in Fig.5. With astonishing precision the cumulative number of papers published is fitted by the epidemologic model. This means the diffusion process is very stable. According to Hägestrand of the University of Lund, this stability is due to the fact that our society, including the scientist's subset, is a *verbal* society where the important information is transferred through the grapevine. The friendly groups are made up of about 100 people, and they tend to be stable in time. Hägerstrand spent his lifework analyzing the processes *on the field*. The situation in the scientific area has been studied independently by de Solla Price, and the conclusions converge.

The stability expressed in Fig.4 is very important because it is at the basis of the *use of the model for forecasting*. My colleagues and I have analyzed perhaps 3000 cases in the spirit of Fig.4, covering all sorts of social activities, and with very very few exceptions the stability principle holds. Even for processes lasting centuries, and I present in Fig.6 one of my preferred examples, the construction of the gothic cathedrals in renaissance Europe. The beauty of the example is the solidity and visibility of the objects, all sitting there to be counted for a crosscheck.

The stability across centuries of diffusion processes is a real puzzle. Wars, pestilences, famine, and political changes, nothing seems to dent it. Perhaps our vision of history is too dramatized and the real dominator is the gray routine. Obviously, if we look with a time microscope, year by year, the effect of a war is visible, but after the impediment is removed systems *catch up* reabsorbing the perturbation and keep going following the previous trajectory. Perhaps the diffusion of *action paradigms* keeps going and only the actions are impeded. Once liberation from impediment comes, the *imprinted ones act*, bringing the system, as *measured by actions*, in line.

The premises done, let us go to the meat of our subject, and start from the diffusion of a product, e.g., the car, just to take a very visible one. The diffusion of the car (number of registered cars) in Europe is reported in Fig.7. We see here two diffusion waves, one reaching 7.5 10^6 at saturation (around 1940) and the second one reaching 150 10^6 cars (around 1995). As the second diffusion wave sits on the first one, the total number of cars around 1995 should be in the range of 160 10^6. The reason why the process is split into two waves is very important for people in R&D and I will treat the problem in detail later on. We can also look at the USA and find the result presented in Fig.8, which is in many ways similar to the European one. The pulses are again two, and the first one tends to 26 10^6 (around 1940), the second adds 125 10^6 cars around the year 2000. The hook due to the recession in the USA is very visible because of the amplification that the Fisher-Pry transform brings on the upper and lower tails. The maximum deviation is in fact less than 10%. The numbers, however, *catch up* once the depression is reabsorbed.

All these cars stem from a large industry producing them. Total production at world level is depicted in Fig.8. But as I said before, the system is fractal so that one can zoom into a single company. The case of Mercedes is reported in Fig.10. The companies actually operating are a slim remnant of a *entrepreneurial wave* which animated the period 1900–1930, when thousands of shops were opened manufacturing all sorts of cars. In a Darwinian sense these shops were a way to test the entrepreneurial fitness of the people behind them. Also that *should* follow the "action paradigm" diffusion model. An analysis for the USA is reported in Fig.11. The full line shows the wave of the founders (cumulative). They finally reached the incredible number of 1400. The dashed line reports the cumulative number of "quits", meaning the entrepreneurs who closed shop for a reason or another. Calculating the $\overline{N}$ by best-fitting the data we get again 1400. The dozen or so who managed to survive are hidden in the computing errors. This is an excellent example of the *holocaust of the entrepreneurs.* The few ones who reached success are applauded. The rest is forgotten. But these failed entrepreneurs are the lifeblood of capitalist economy. They try all ways and they are the basis for the choice of the best the market will do. The choice of the best means that, later on, the product will be manufactured more economically than in the case of no choice, presumably overcompensating *at system level* the losses that come from broken initiatives.

We jump into our times, in order to show business as usual after half a century. Newcomers in the area of *mainframe computers* are reported in Fig.12. They are monitored in terms of having marketed at least one computer model. They seem to saturate around 700, a number in the same ballpark of the 1400 car manufacturers. Computer manufacturers are now about a dozen big ones, with a dust of small ones appearing and disappearing. The final shake-down may bring the total to a handful again.

It is very difficult to get data on R&D *per se*, but we may look at the business end, and measure, e.g., the number of models that enter the market as a kind of proxy. The analysis is reported in Fig.13 for the cumulative number of new *mainframe computer models* put on the market. We can glimpse here into one of the forecasting procedures that can help the R&D manager to define his strategies. What Fig.13 says is that the bandwagon is running at full speed and will be running (at decreasing speed) for another 20 years. To jump in or not depends on his judgment, obviously, but the tip given by the chart in Fig.13 is sharp and quantitative.

Let us now come to the reason why car penetration of Fig.7 and 8 had two pulses. I will arrive there through the tortuous way I originally drove to discover Kondratiev cycles. My original problem was to map invention and innovation along history, using some model to evidence the taxonomy and to search for invariants. At that time (1979) I had the lists of basic inventions and innovations Mensch had elaborated. They had a special merit to my eye, that the dates nailing them to historical times were obtained using a homogenous procedure. Invention is the date when the prototype works. Innovation is the date when the first commercial product is sold. Mensch's lists have been criticized in many ways, e.g., by the fact that they are not complete. This is certainly true, but the analysis as I will make it operates equally well on (significant) samples, and Mensch's lists appear to be a good sample as the analysis itself implicitly shows.

The hypothesis was that these "action paradigms" can be very abstract indeed (fractality!) and operate, e.g., at the level ["invent"] or ["innovate"] (as for building gothic cathedrals), presumably with descriptors we do not know. *If* this is true, *then* the cumulative number of invention and innovation in *each* of the pulses Mensch had identified should be fitted by a diffusion equation. The first wave invention–innovation is shown in Fig.14. The idea obviously works. One can repeat the analysis on the other two couple of waves, again as identified by Mensch, obtaining similar results. The synoptic table is reported in Fig.15 in simplified form, i.e., stripped for simplicity of all numerical indications. The taxonomy of the three pulses is full of internal constraints, so much that I could calculate the fourth wave, at least taxonomically, i.e., for what refers to time structure but without knowing the saturation point ($\overline{N}$).

The analysis of Fig.15 had many spillovers. One is that the center-points (t_0) of the innovation waves are 55 years apart. These 55 years lead me to discover Mr. Kondratiev and his cycles. As further analysis did show, 55 years pop up everywhere when we study the behavior of our system. Measuring the cycles from the troughs (1940), (1995), we see, e.g., that most saturations "lean" against the trough as one can see for the cars of Fig.7 and Fig.8. Another very important observation is that most innovative activity occurs near the troughs. To give more visibility to the situation, I report in Fig.16 an analysis of the residuals of total energy and electricity consumption in the USA done by Stewart (Fig.16). The residuals are percentage deviations from a long-term best-fit (logistic) of energy consumption in the USA. The ascending branches of this quasi sinusoid fit well with booms and the descending one with recessions (and occasional depressions). We can take this "energy clock" as a reference to position other facts, e.g., the centerpoints (t_0) of invention and innovation waves (Fig.17). We see the curious fact that innovation centerpoints are always located in the same position in the wave, very near the trough. Invention waves centerpoints, on the contrary, keep changing phase position approaching progressively innovation centerpoints.

Just to show that innovation positioning is not just a freak, the case of the construction of large transportation infrastructures in the USA is reported in Fig.18. This time the presentation of the logistic is in linear ordinates (%) as in Fig.2. The centerpoints of the three waves, canals, railways, and paved roads, lie exactly 55 years apart, and their phase is obviously stable, 6 years after the troughs (1830–1885–1940). The important point for us is that we live in an innovation window, and the taxonomy is reported in Fig.19. The centerpoint is in 1993 and 80% of it is between 1984 (10%) and 2002 (90%). *Messieurs faites vos jeux!* The basic inventions wave instead is almost out (90% in 1987). A taxonomic peculiarity is that each innovation wave is associated with the beginning of the market penetration of a new primary energy source (we had coal, oil, and gas for the previous three). Ours seems linked to nuclear energy (1% of total energy market in 1972). The fact that this penetration, real, fits well the innovation wave, calculated, lends credibility to our extrapolation (forecasting?).

There are certainly a number of hints that R&D managers can extract from these charts, in relation to the general envelope to give to their program. But is it possible to zoom into finer details of the swamp where research people have to muddle through?

I have said the system is fractal, so we can zoom, and an example was already given in Fig.5. I may have analyzed perhaps 150 similar cases, so CO_2 does not sit alone. The example here refers to biomedical research: Vitamin D metabolism (Fig.20). The papers quoted here are not "coloring book" activity like most scientific publications. They represent real progress and ISI made an effort to identify them through citation. In a sense they map the level of exploitation of the "vitamin D metabolism" field. It is already empty, so that unless a new basic idea breaks new ground, it is not worthwhile to enter into it.

But let us move now to more near-to-industry items. A couple of years ago I undertook a study for the EEC, trying to map the situation of R&D in *materials.* I will pick some of the analysis from there. The case of *Rare Earth Cobalt Magnets*, to give an example, is reported in Fig.21 in terms of publications. (Source: Chemical Abstracts, from which I take the notation "non-patents" meaning publications.) It is clear that the subject is out, at least for what concerns basic research (a second go is possible, but it has to be started). For what concerns R&D intensity I took patents as a proxy. They come in two waves, one centered in 1975, already finished and the second centered in 1988. There is s till some space there, although the time constant of 9 years makes it tight. Generally speaking R&D managers *or* they start something really new, *or* they must have very fast reflexes. The time constants for bandwagon runs usually cluster around 10 years.

A material into which a lot of attention has been concentrated is PVC.

It is flexible, cheap, and potentially dangerous. The analysis of publications is reported in Fig.23. The numbers are indicators of the interest and fertility of the subject. Papers number 8500 in the first go and 2000, at saturation, in the second. The number of patents is deployed in a single go, and we are at present still very near the point of maximum rate of patent production (Fig.24). The leasury 22 years for the time constant leaves a chance for the late-hour joiners.

One can wonder how an analysis of past rates can forecast what is left. The interpretation behind is that the rate at which a class of children finds mushrooms in a wood is a measure of the number of mushrooms left. To this objective I show a post-mortem analysis of the discovery of the chemical elements, a process which lasted for a couple of hundred years (Fig.25). They are the elements not already known in current practice since antiquity, like iron, copper, silver, or gold or sulfur. Obviously the search has to be connected to the methodology. Microscopic mushrooms are not picked by the boys. We see three waves. The point is that when a wave is halfway we can fit it with a logistic and predict saturation. Thus in 1880 we could have predicted that 25 elements ($\pm$) could yet be discovered, *and when*. A more amusing (and more precise!) game would have been to bet for the date of discovery of the next one.

That said let us come back to our PVC and look, e.g., at the last leg after R&D: production (Fig.26). Here we specialize on PVC for pipes, the most important application, and for the USA. The "noise" is fairly high but the trend is neat and saturation should occur around 1995 (end of Kondratiev) at the level of 1.1 10^6 cubic meters. We can also zoom back and look at plastics in general as materials for pipes (Fig.27). The analysis shows that at saturation (around 1995!) the volumetric percentage of plastics in pipes will be about 70%. There are obviously hindrances for substituting plastics for metals or ceramics in certain fields, and this can be a fruitful basis for R&D.

I can certainly continue presenting examples for hours, but the objective of this presentation is to make you aware of the existence of a methodology that can improve on the present situation when faced with the problem of programming into an uncertain future. Properly used, this methodology can reduce by an order of magnitude the uncertainties that come from an intuitive evaluation even when formalized and mediated, e.g., in Delphi procedures. It must be clear that I have the greatest respect and admiration for intuitive hunches, but science can do better. After having heard about the methodology you can dig deeper, and for that purpose I add a bibliography, trying to help in that direction. Forecasting, as a science, is always an art, but we are constructing rules.

The most important consequence of the exploration that my colleagues and I have done using the "*action paradigm*" diffusion concept on the taxonomy of social systems is that *everywhere we look we find order.* Through a very complex set of informational (mainly verbal!) feedbacks our system stays highly organized, in spite of the apparent disorder we perceive. And it stays the same, i.e., it conserves its internal identity for such long periods of time that the conclusion it is a superindividual is almost inescapable. In the spirit, but more precisely than the Leviathan of Hobbes. In this context the role of R&D has precise boundaries and fine channels leading to success. Identifying them well reduce the very high cost of trial and error procedures.

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Fig.1.

Epidemics run as shown here, if we look at new entries. The growth on the left side of t_0 depends on the amount of infected who can spread the plague, the decrease on the right side depends on the progressive shortage of infectables. The maximum rate of growth of t_0 is when infected and infectable are more or less equal in number.

Fig.1.

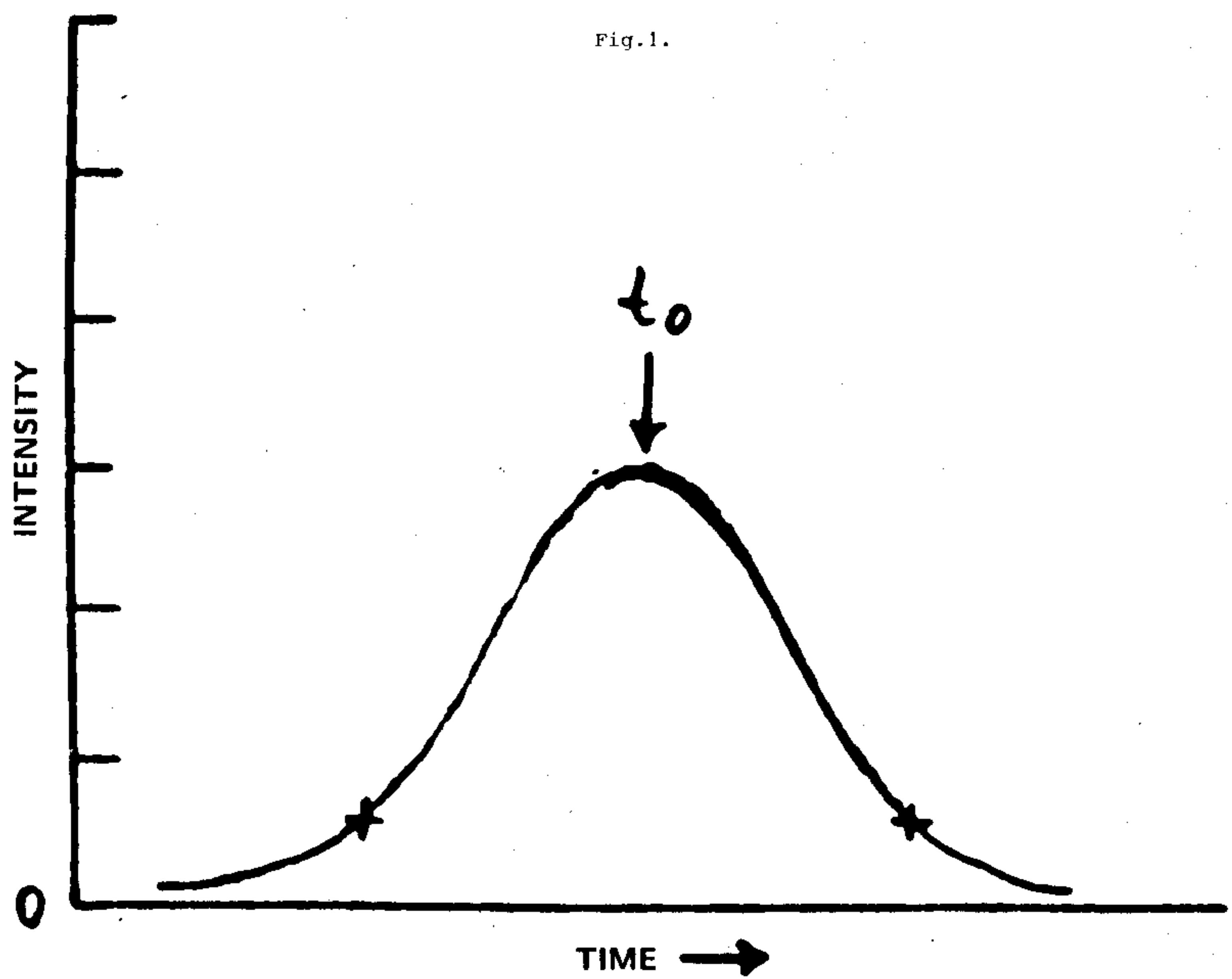


Fig.2.

If we integrate the curve of **Fig.1** we get the cumulative number of infected, here normalized on the total number of infectables taken as 1, or 100%. The two crosses indicate 10% and 90% level. The curve is the well-known *logistic* extensively used in biology and ecology (as a simple solution of the Volterra-Lotka equations of competition).

Fig.2.

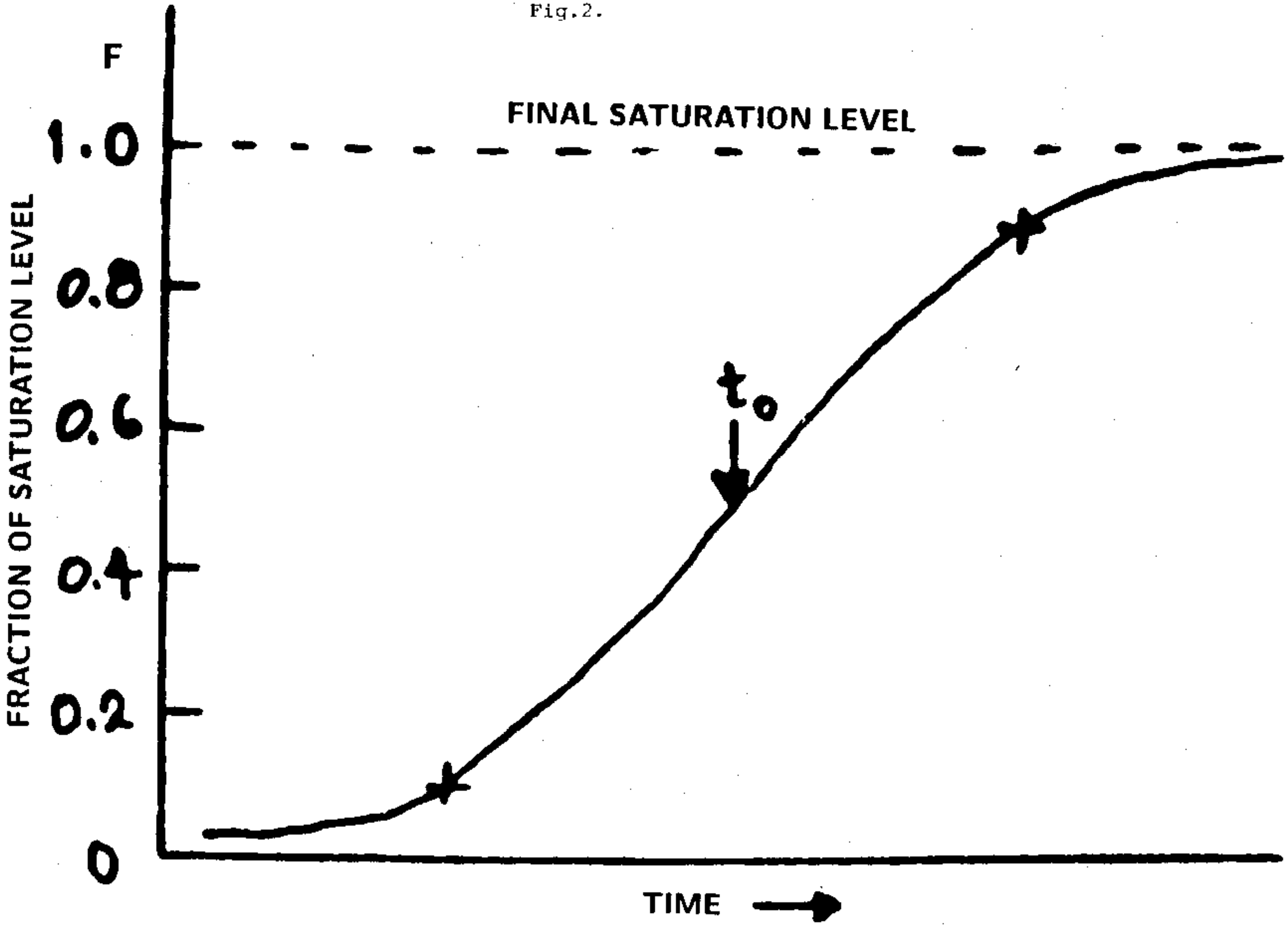

F
FINAL SATURATION LEVEL
1.0
0.8
0.6
0.4
0.2
0
FRACTION OF SATURATION LEVEL
t0
TIME

Fig.3.

In the text the logistic of Fig.2 will be represented with the Fisher-Pry transform, where by manipulation of the ordinate we get a straight line. Crosses and t_0 have the same meaning as in Fig.2. The saturation point is given here as a number in parenthesis. The rate of the process as a ΔT, the time to go from 10% to 90%.

Fig.3.

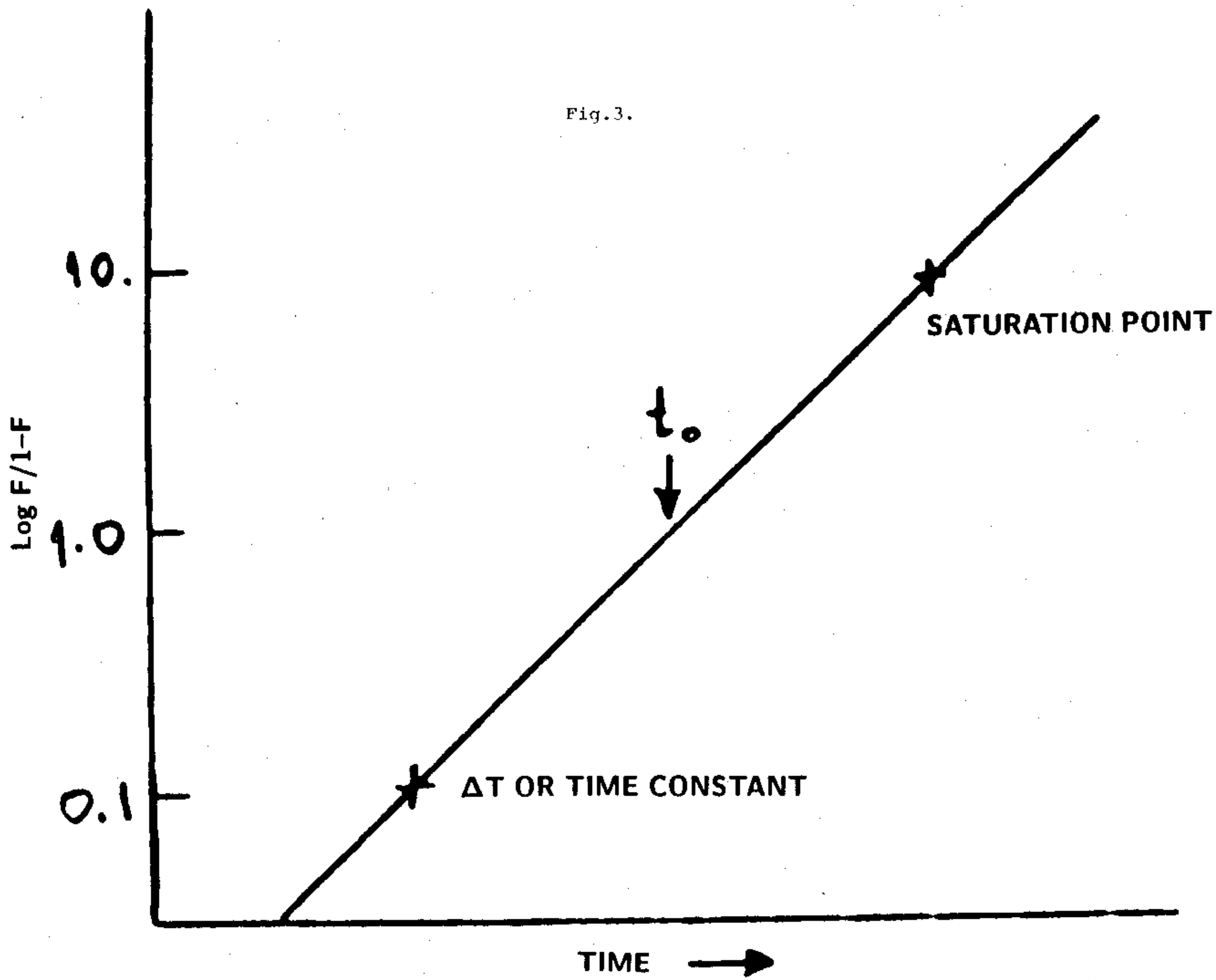
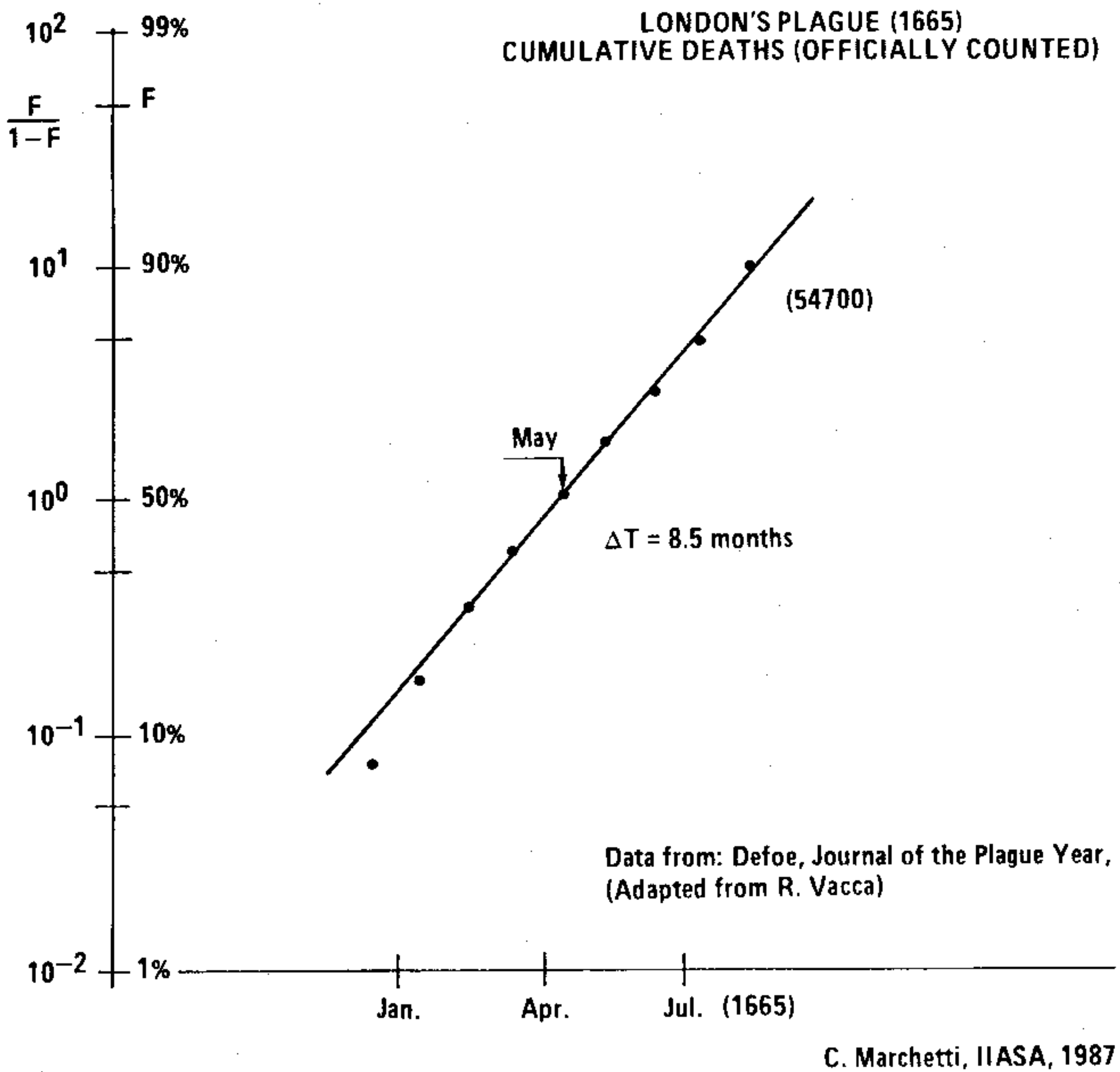


Fig.4.

Counting deaths seems a good proxy for counting people falling ill, the real object of epidemological diffusion. In spite of the extremely complex network of personal (and flee) contacts that bring the diffusion of a plague, the result is very neat and fits well the diffusion equation of Fig.3.

Fig.4.



LONDON'S PLAGUE (1665)
CUMULATIVE DEATHS (OFFICIALLY COUNTED)
10^2
99%
$\frac{F}{1-F}$
F
10^1
90%
10^0
50%
10^{-1}
10%
10^{-2}
1%
(54700)
May
ΔT = 8.5 months
Data from: Defoe, Journal of the Plague Year,
(Adapted from R. Vacca)
Jan.
Apr.
Jul.
(1665)
C. Marchetti, IIASA, 1987

Fig.5.

I did not aim at irrespectful associations, but a plague can be seen as the diffusion of a message, as in the case of the interest the scientific community takes in the connections between CO_2 in the atmosphere and climate. The final product of scientific interest is a paper, and, as in the case of London's plague, counting the papers cumulation points neatly to a diffusion process at work.

Fig.5.

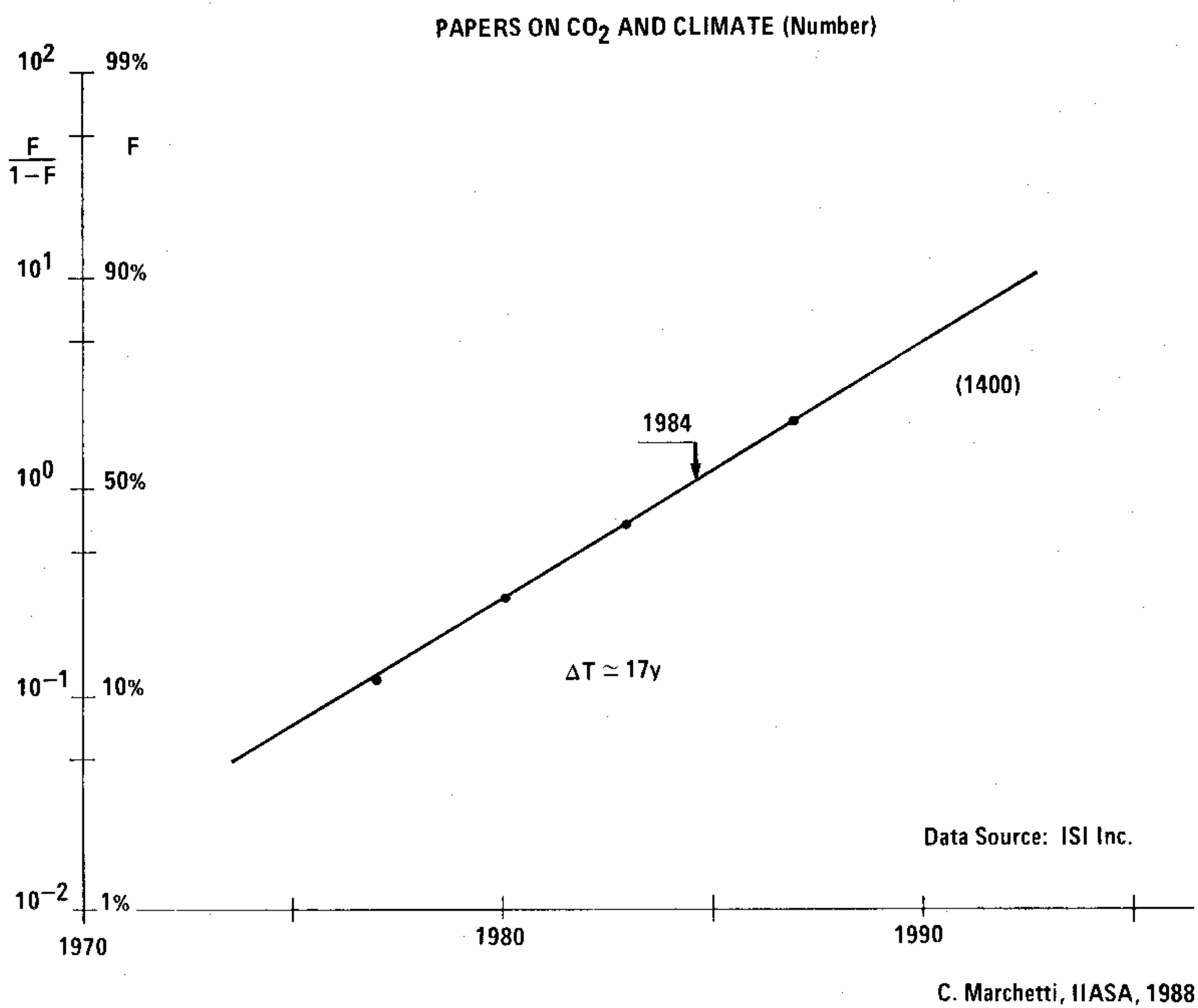
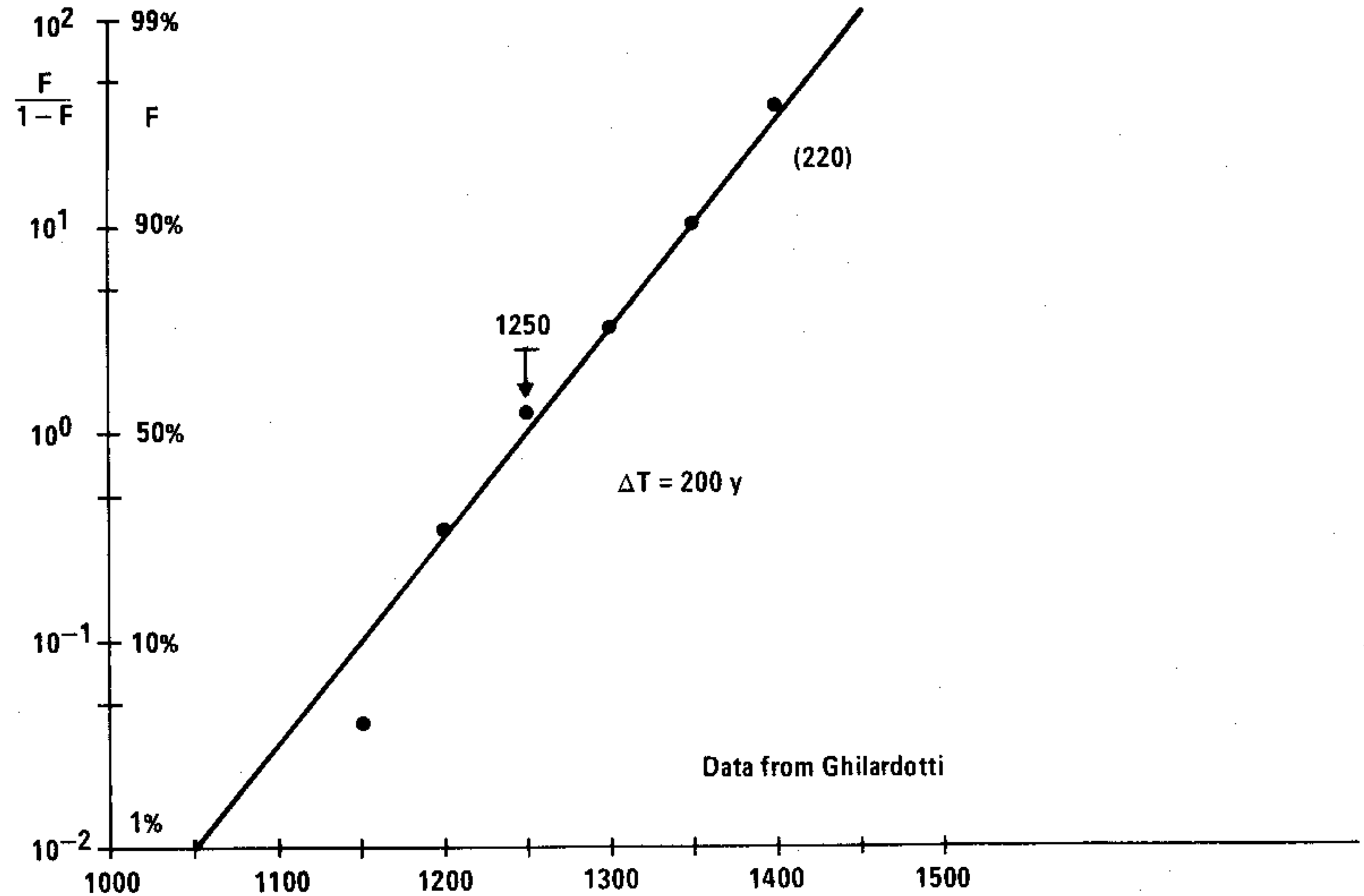

PAPERS ON CO_2 AND CLIMATE (Number)
10^2
$\frac{F}{1-F}$
10^1
10^0
10^{-1}
10^{-2}
99%
F
90%
50%
10%
1%
1970
1980
1990
1984
(1400)
$\Delta T \simeq 17y$
Data Source: ISI Inc.
C. Marchetti, IIASA, 1988

Fig.6.

This is my preferred example to show the long-term stability of cultural diffusion processes. In this case it did hold to its equation for almost four centuries. Here there are no proxies. The cathedrals are there to be counted.

Fig.6.

GOTHIC CATHEDRALS IN EUROPE



C. Marchetti, IIASA, 1985

Fig.7.

The diffusion of cars in Europe is here depicted for almost one hundred years with great economy of parameters (three per equation). The sharp delimitation of the saturation times around 1940 and 1995 shows the great importance of economic long cycles (Kondratiev) in determining the behavior of the adopters of a new technology.

Fig.7.

CAR CIRCULATION IN EUROPE (Millions)

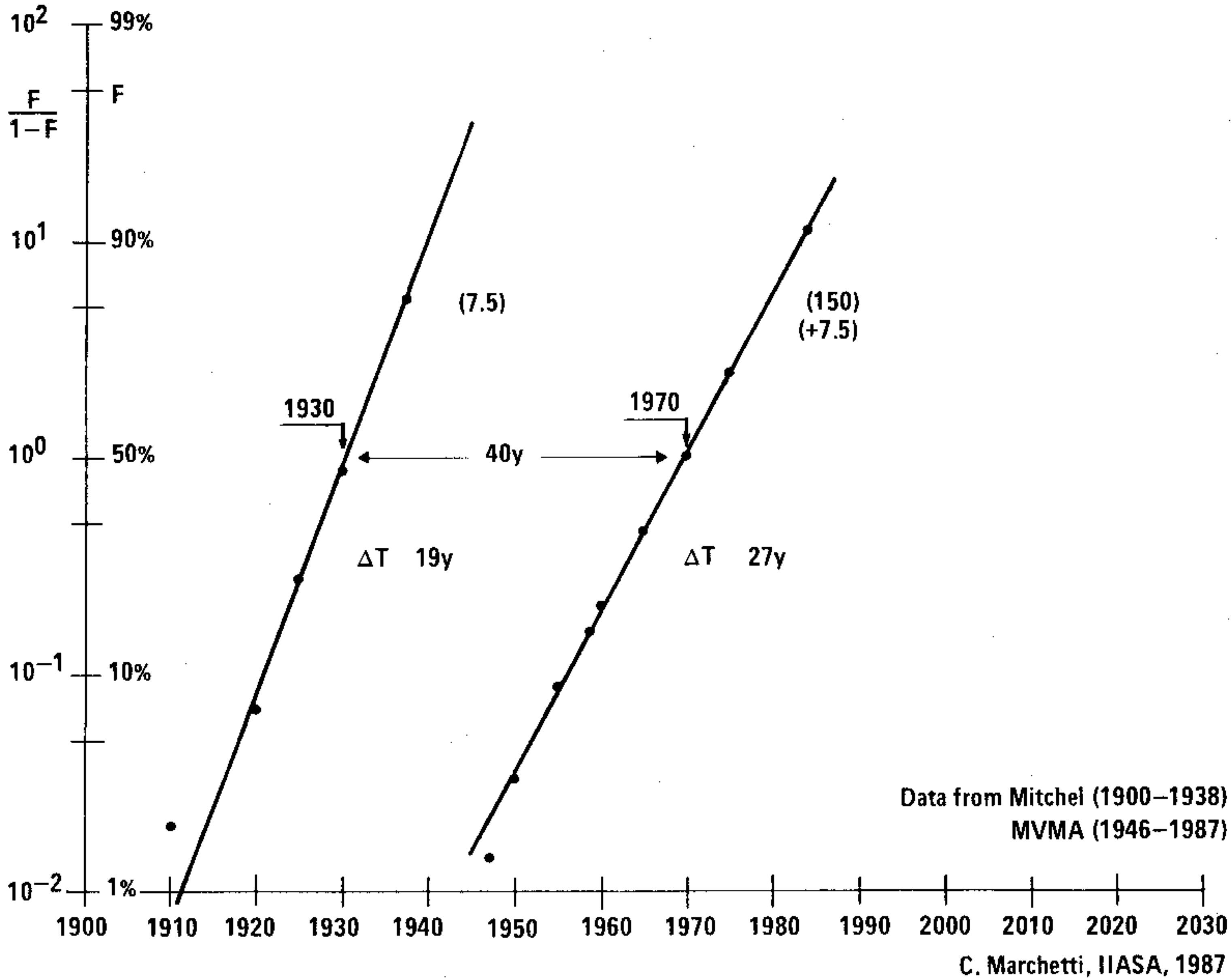


Fig.8.

The same as in Fig.7 but for the USA. Note the big hook due to the deep recession of the thirties and its reabsorption when the depression was reabsorbed.

Fig.8.

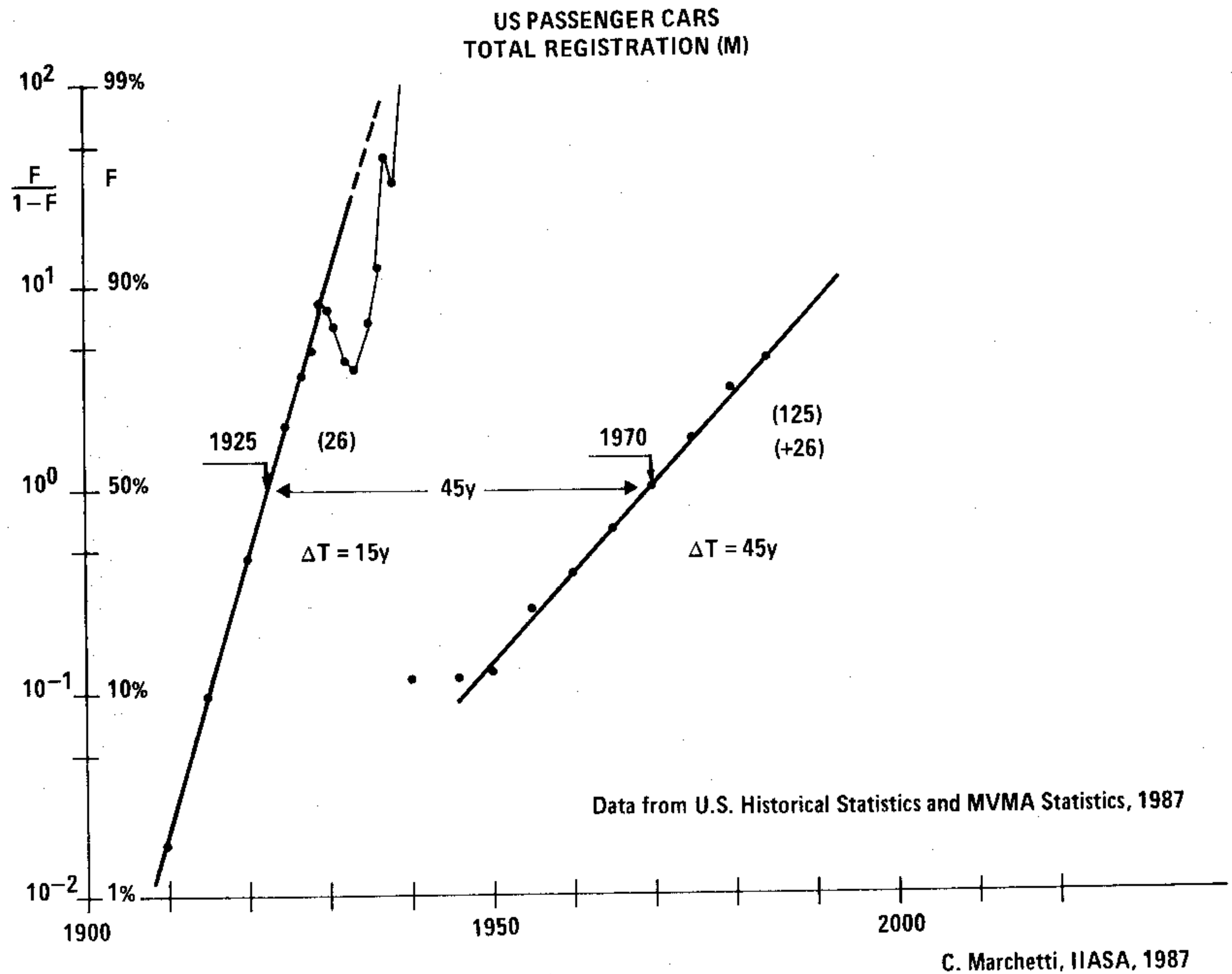
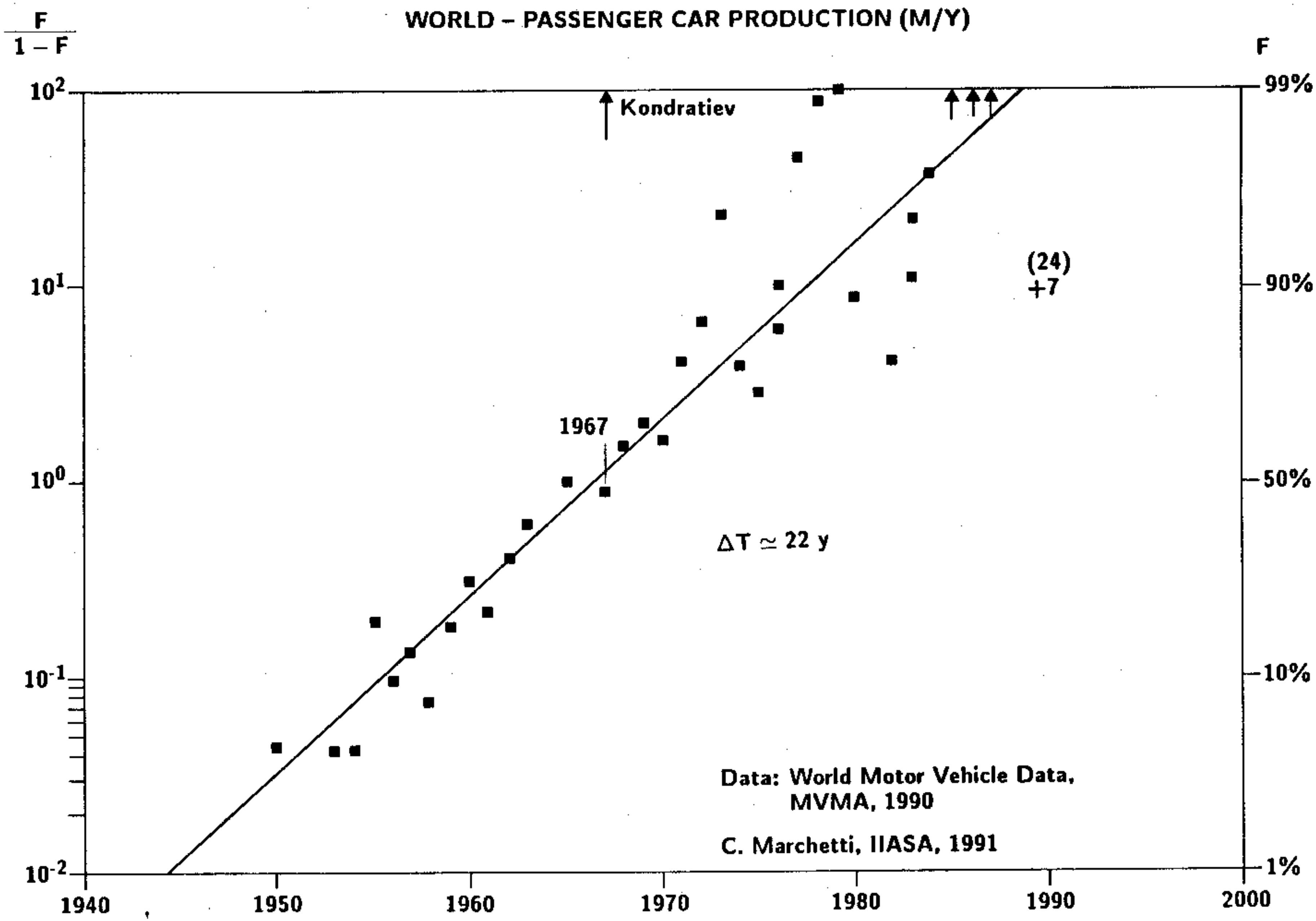

US PASSENGER CARS
TOTAL REGISTRATION (M)
10^2
99%
$\frac{F}{1-F}$
F
10^1
90%
10^0
50%
10^{-1}
10%
10^{-2}
1%
1925
(26)
45y
1970
(125)
(+26)
ΔT = 15y
ΔT = 45y
Data from U.S. Historical Statistics and MVMA Statistics, 1987
1900
1950
2000
C. Marchetti, IIASA, 1987

Fig.9a.

The expansion of car production is a second level effect of diffusing the idea of operating and owning a car to increase personal mobility. It can be mapped fairly well with a logistic equation. But the noise level is high.

Fig.9a.



WORLD – PASSENGER CAR PRODUCTION (M/Y)
F / 1 – F
F
10^2
10^1
10^0
10^-1
10^-2
99%
90%
50%
10%
1%
1940
1950
1960
1970
1980
1990
2000
Kondratiev
1967
(24)
+7
ΔT ≃ 22 y
Data: World Motor Vehicle Data,
MVMA, 1990
C. Marchetti, IIASA, 1991

Fig.9b.

In order to better visualize the “noise” in the statistics of car production, the percentage deviation of actual data from the fitted logistic of Fig.9a is reported here. As already said, the noise is high as deviation can be in the order of 10%. However, integrating the logistic and the actual data from 1950 to 1985, the difference is only a fraction of 1%. This shows that the logistic is *the* carrier by respect to which deviations are elastically reabsorbed.

Fig.9b.

WORLD – PASSENGER CAR PRODUCTION

Deviations from logistic – 1967, $\Delta T \simeq 22$ y [(24) + 7] M

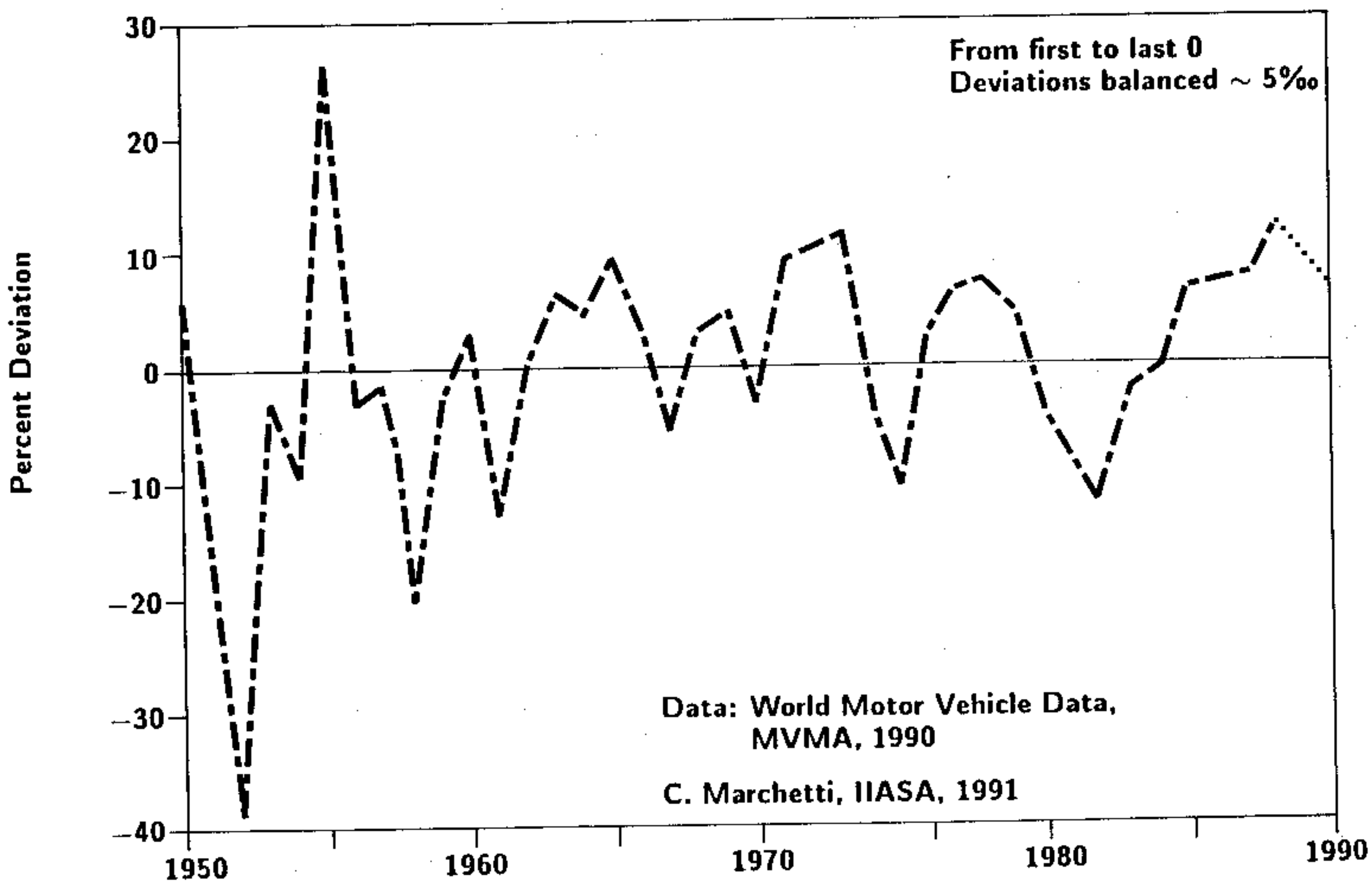
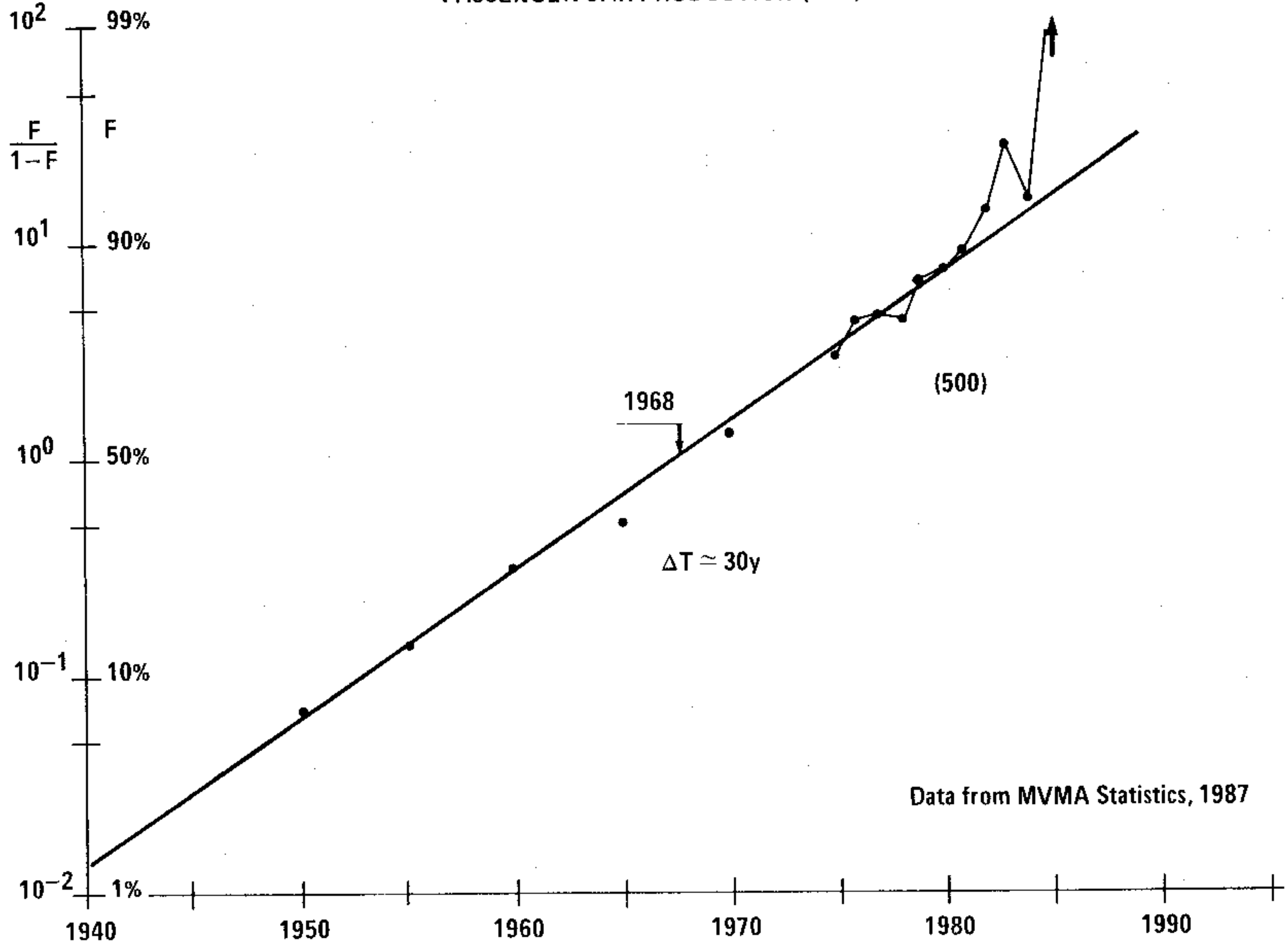


Fig.10.

The logistic growth of the world market is mirrored in the logistic growth of a single company, Mercedes, in this example. We can interpret the process as a diffusion of the image of Mercedes into the heads of potential customers. As innumerable examples show, the *system learns slowly.* (In typical processes 55 years is a good time scale.)

Fig.10.
GERMANY – MERCEDES
PASSENGER CAR PRODUCTION (.000)



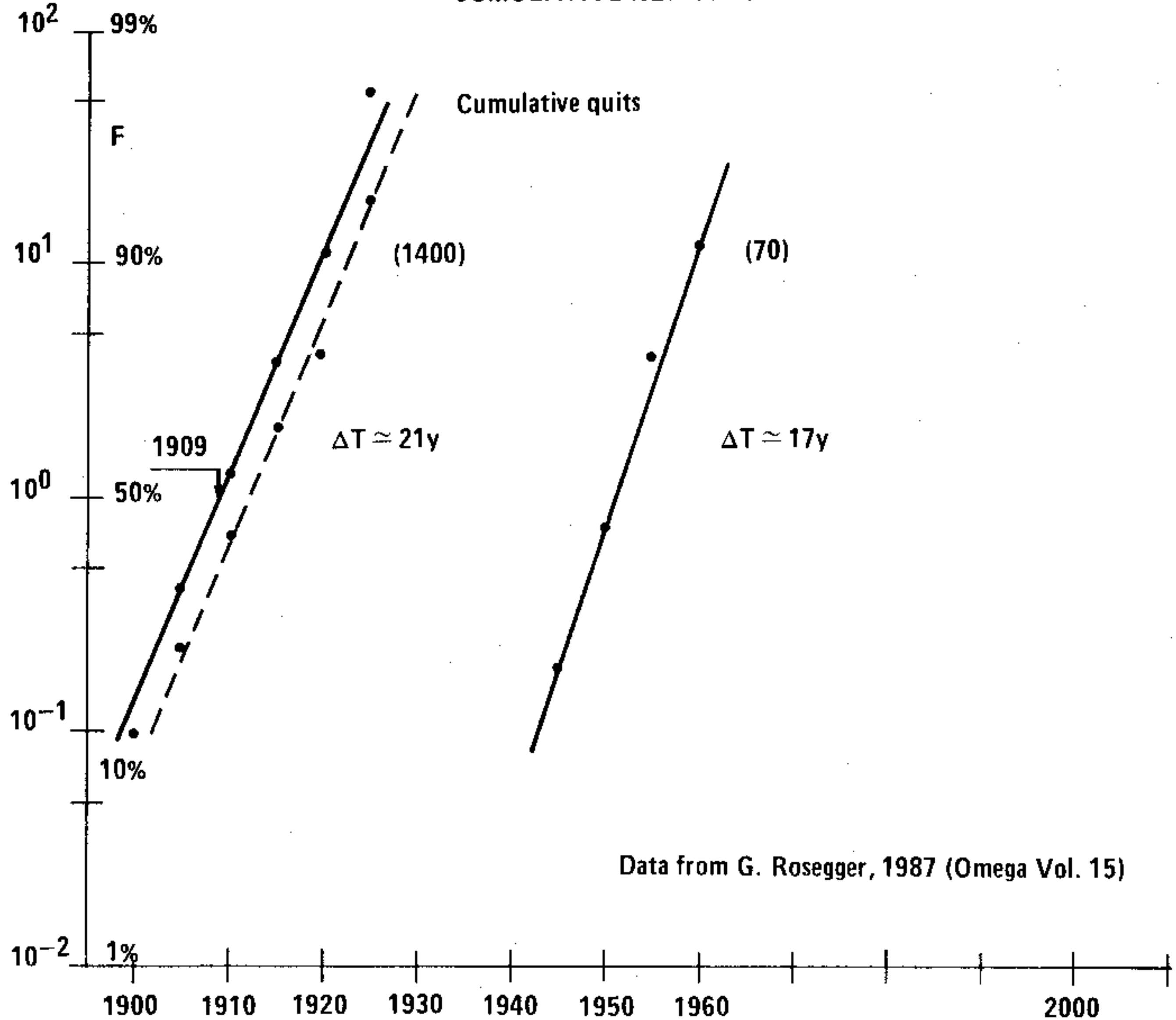
C. Marchetti, IIASA, 1987

Fig.11.

Zooming one step back from car-producing companies, we have entrepreneurs founding companies. Counting companies that entered the market in the first half of this century in the USA, we find two logistic pulses. The first one cumulates to 1400 (full line). Counting the number of companies that disappeared from the market we get a similar cumulative count (dashed line) and time constant. The distance between the two lines is 4 years, the mean lifetime of these entrepreneurs. Out of 1400 about a dozen survived.

Fig.11.

US – CAR MAKES
CUMULATIVE NEW ENTRIES



C. Marchetti, IIASA, 1987

Fig.12–13.

One may think that such peculiar behavior is characteristic of the free market and ruthless capitalism of America at the beginning of this century. To dispel the suspicion I report here the case of *Mainframe Computers* analyzed at world level.

In Fig.12 the growth of the number of computer makers that entered the market at least with one model is reported. Their cumulative numbers grow logistically and saturate to 700, a number in the same ballpark of US car makers. The maximum entrepreneurial activity is *right now.* We can expect a dozen to survive Darwinian selection. The larger ones in operation now are about a dozen, but some will die jumping through the Kondratiev trough (1995). In Fig.12 the growth of computer *models* produced by all makers is reported (cumulative number). They will saturate around 3000 (models). Also this innovative activity is in the state of maximum intensity now. The formal peak was in 1987.

Fig.12.

POPULATION OF NEW COMPUTER MANUFACTURES

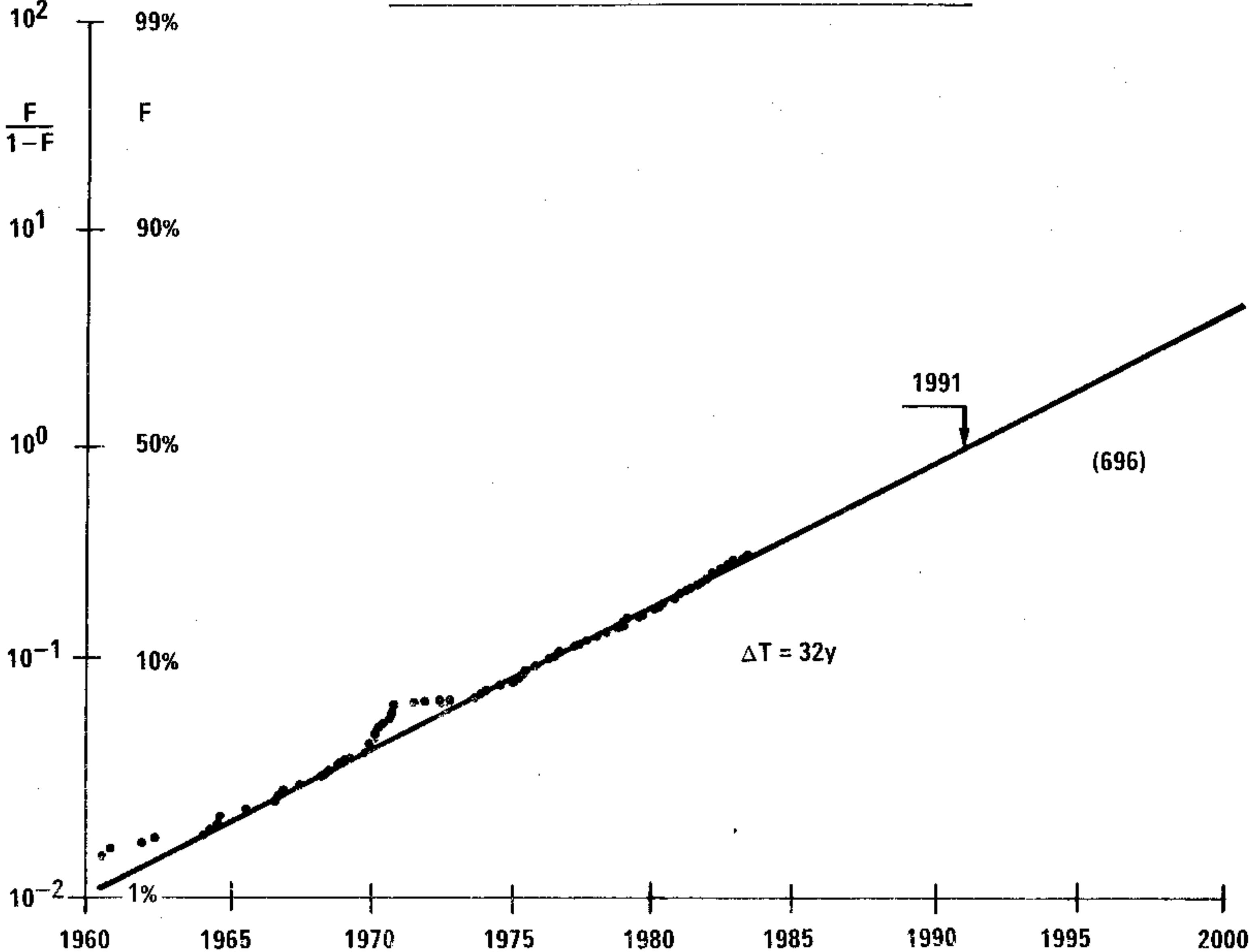


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Fig.13.

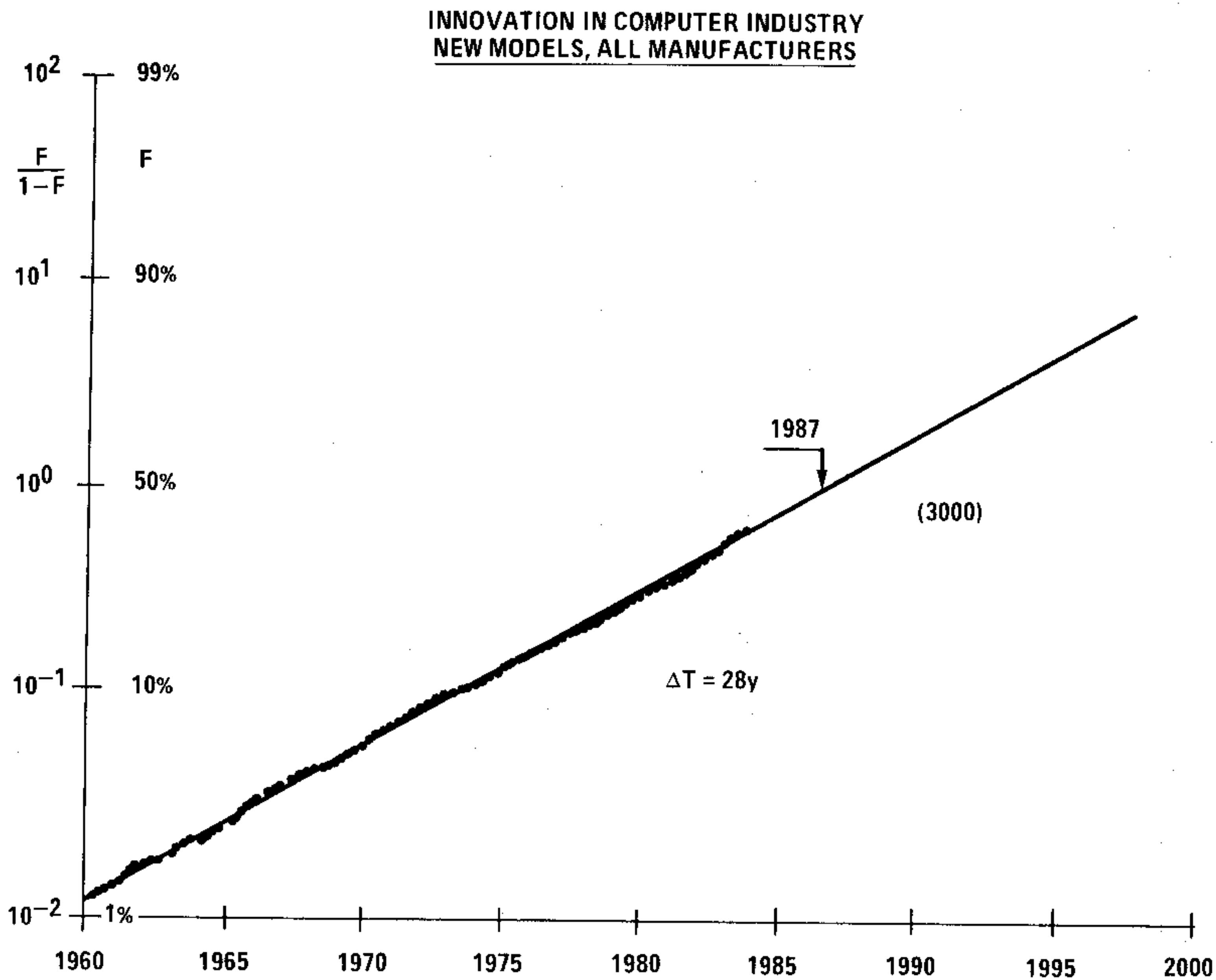

INNOVATION IN COMPUTER INDUSTRY
NEW MODELS, ALL MANUFACTURERS
10^2
10^1
10^0
10^{-1}
10^{-2}
$\frac{F}{1-F}$
F
99%
90%
50%
10%
1%
1987
(3000)
$\Delta T = 28y$
1960
1965
1970
1975
1980
1985
1990
1995
2000

Fig.14.

Invention and innovation activity seen in historical perspective are quite ordered and well-regulated operations. Both come in waves and each wave can be organized as if it were a diffusion wave of a quite abstract action paradigm [time to search!]. The data were collected by Mensch and they should be considered as a sample more than a complete set. The first wave of inventions and of the innovations that come out of them is analyzed here. Only inventions that led to innovations are reported. The analysis fixes in a few numbers the taxonomic characteristics of the wave.

Fig.14.

THE 1802 WAVE

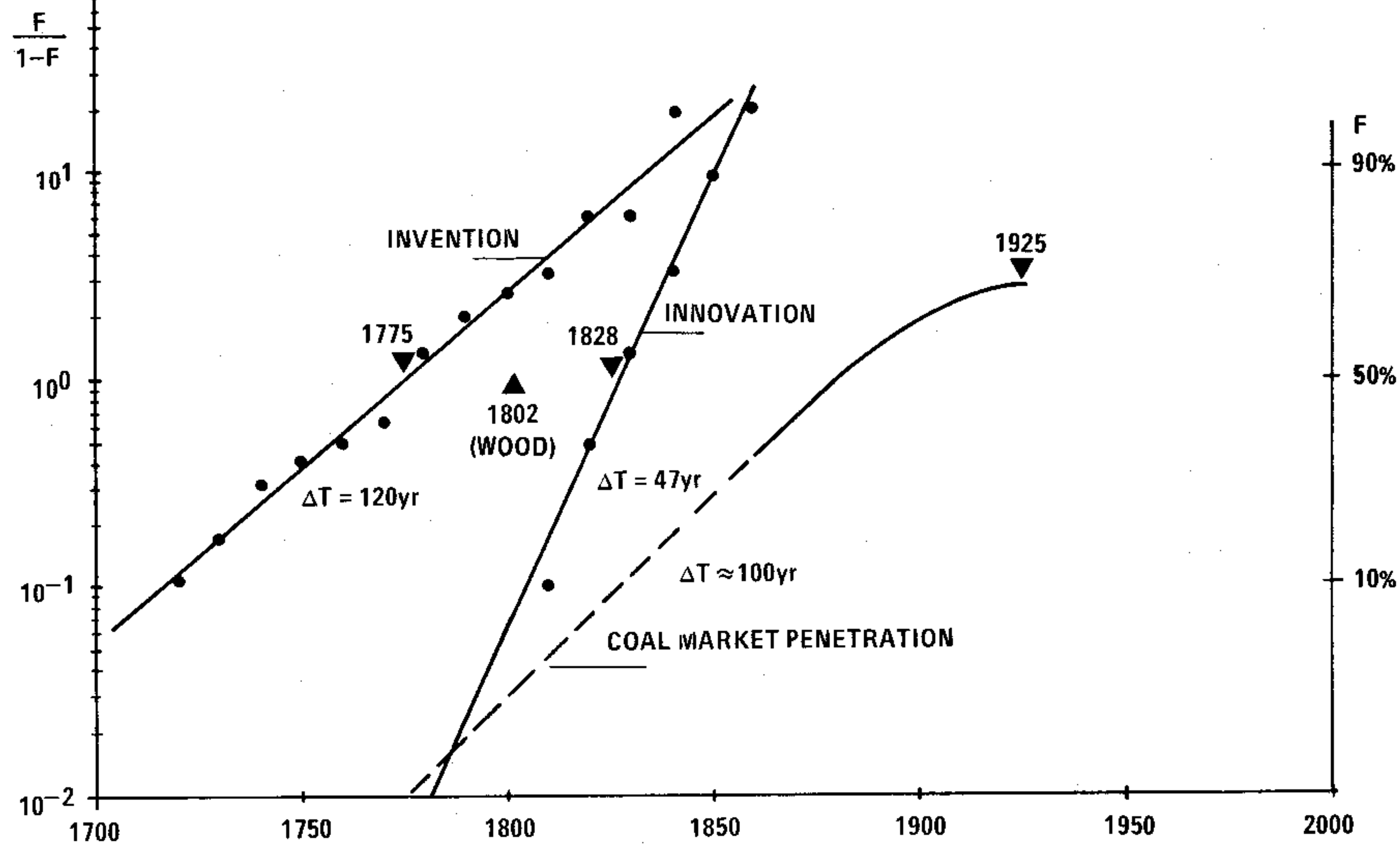


Fig.15.

Mensch recovered three waves of invention–innovation, analyzed as in Fig.14 but reported here in stripped form to keep the chart readable. The taxonomic constraints of the first three waves, plus information coming from the general taxonomy of the system, permit calculating the fourth wave. One of the taxonomies is that the distance between centerpoints of innovation waves is always 55 years, one Kondratiev cycle.

Fig.15.

INVENTION AND INNOVATION WAVES — THE SECULAR SET

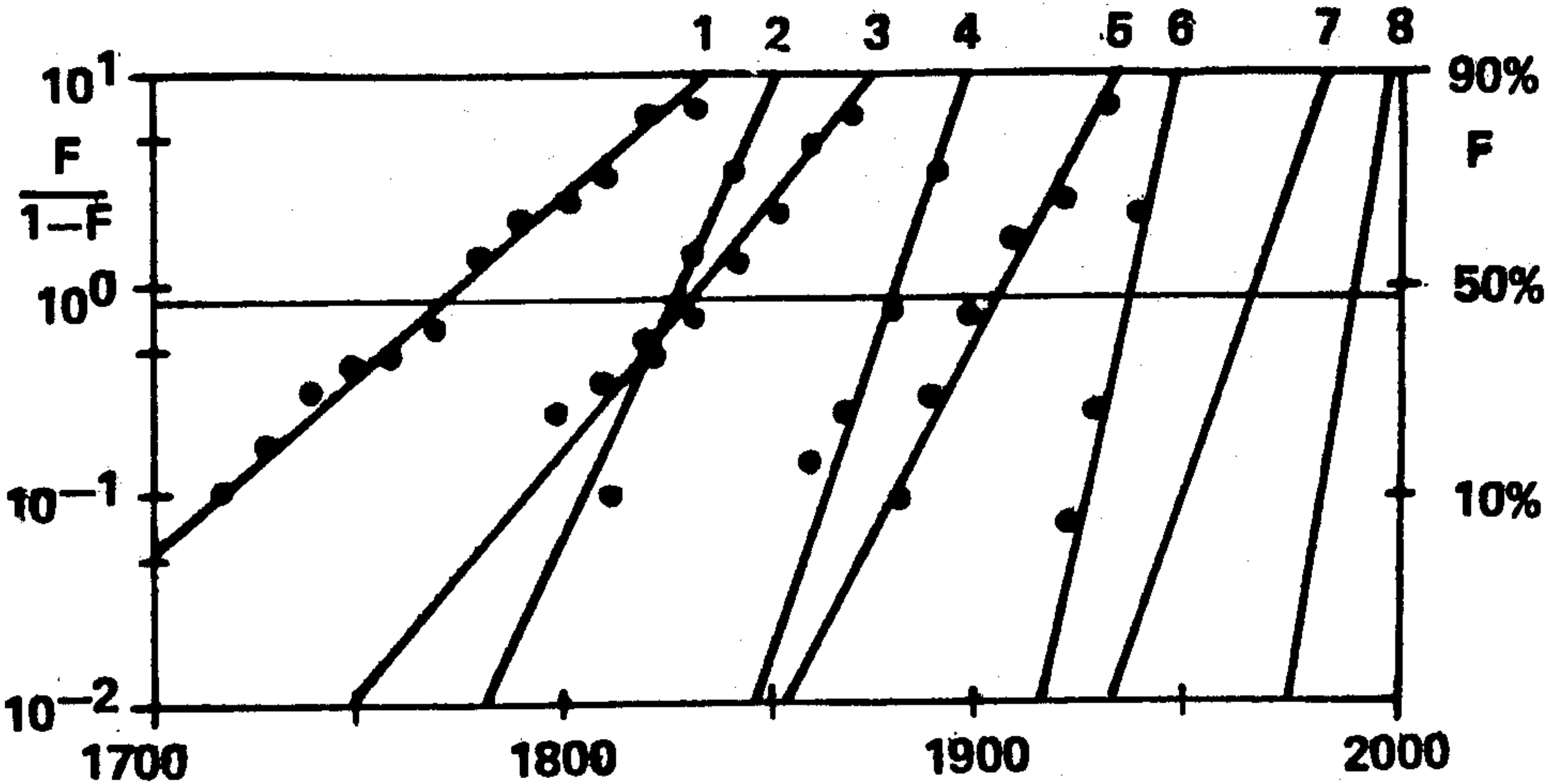
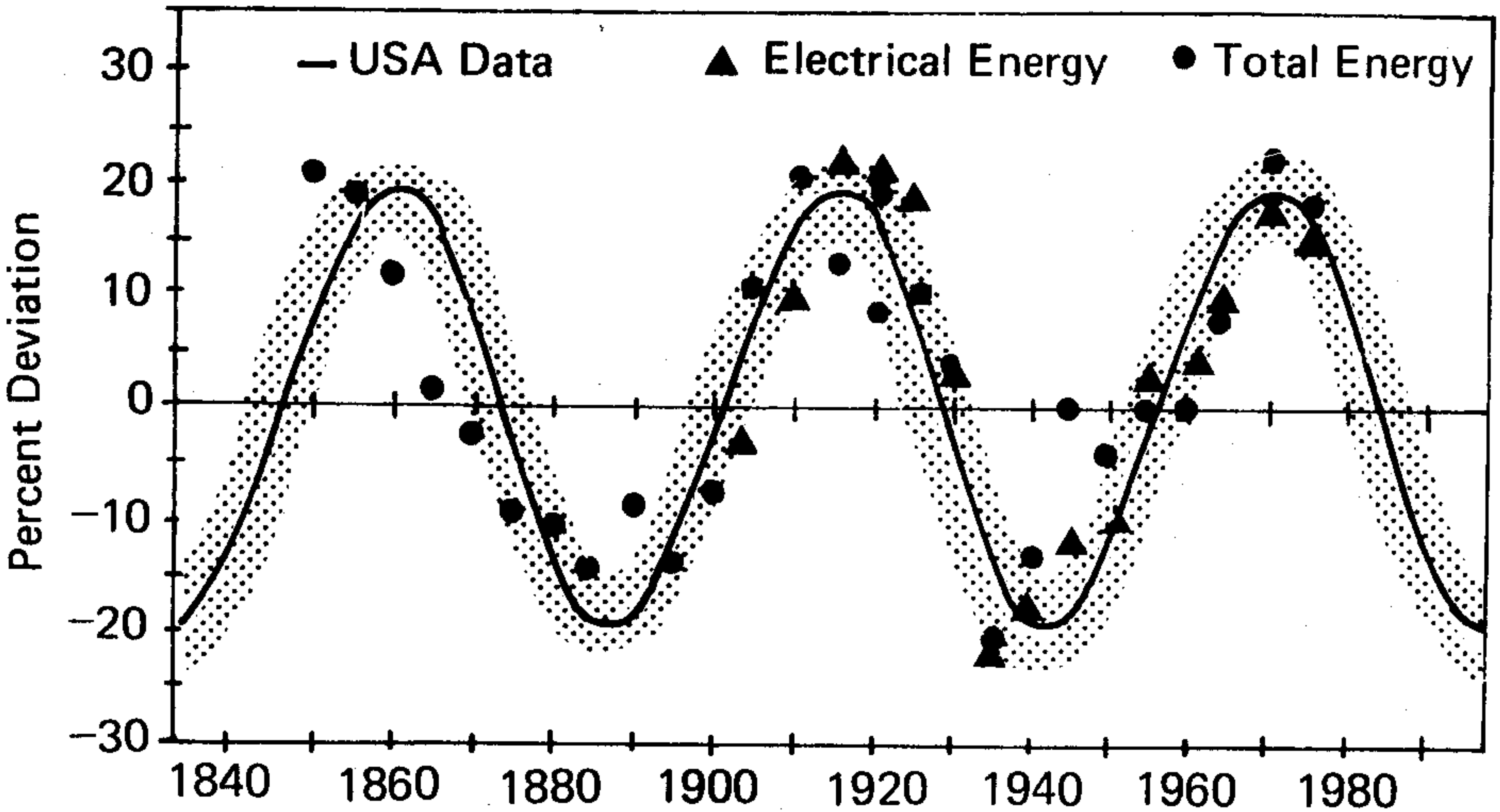


Fig.16–17.

Stewart analyzed the deviations of primary energy and electricity consumption in the USA, by respect to a best-fit of historical data using an interpolating logistic. The result is reported here and shows a consistent quasi-sinusoidal oscillation around the fit with an amplitude of about 20%. This for primary energy *and* electricity consumption. Energy consumption is a good indicator of general activity as it penetrates everywhere mediating all the pluses and minuses. *The period is 55 years* pointing to a precise locking with the Kondratiev cycle. I assumed in fact that the trough in the oscillation coincides with the end of the Kondratiev and made some constructions out of that. One of them is reported in Fig.17 showing the positioning of the centerpoints of the previous three waves of invention and of innovations. Innovations appear locked to the wave but inventions keep shifting their phase advancing toward innovations.

Fig.16.



USA Data
Electrical Energy
Total Energy
Percent Deviation
30
20
10
0
−10
−20
−30
1840
1860
1880
1900
1920
1940
1960
1980

Fig.16–17.

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Fig.17.

CENTER OF INVENTION AND INNOVATION WAVES
LOCATED ON ENERGY INDICATOR

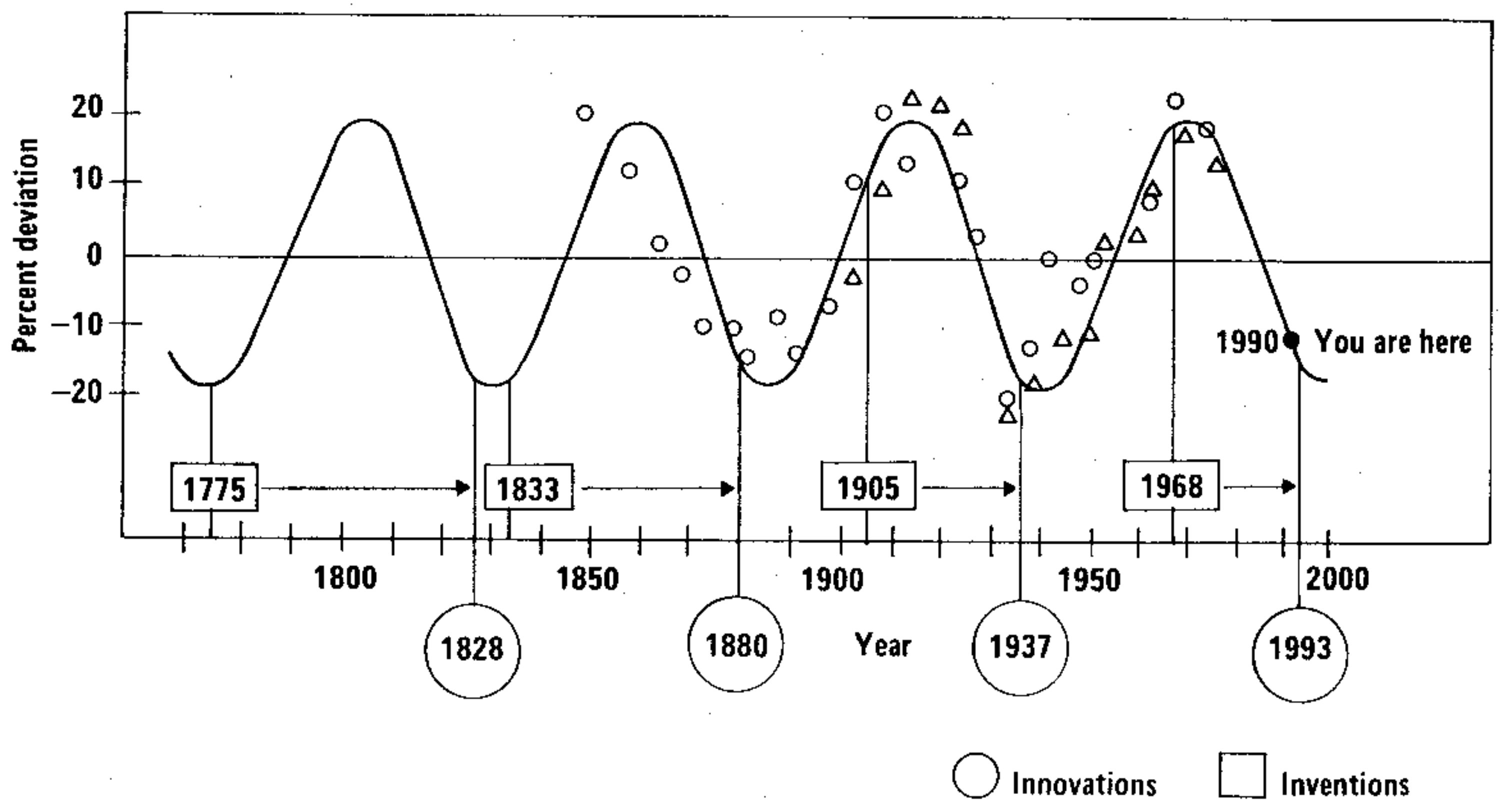


Fig.18.

To give another very macroscopic case of fast locking with Kondratievs. We report here the growth of three transport infrastructure systems in the USA: canal, railways, and paved roads. They are measured as percentages of their final length, and presented in linear coordinates (no Fisher-Pry transform). Their centerpoints are 55 years apart, and are locked 6 years after the troughs. That the activity in infrastructure construction is the Keynesian patchwork recipe to alleviate recession is well known, but all that precision in the long-term construction activity was at all unexpected.

Fig.18.

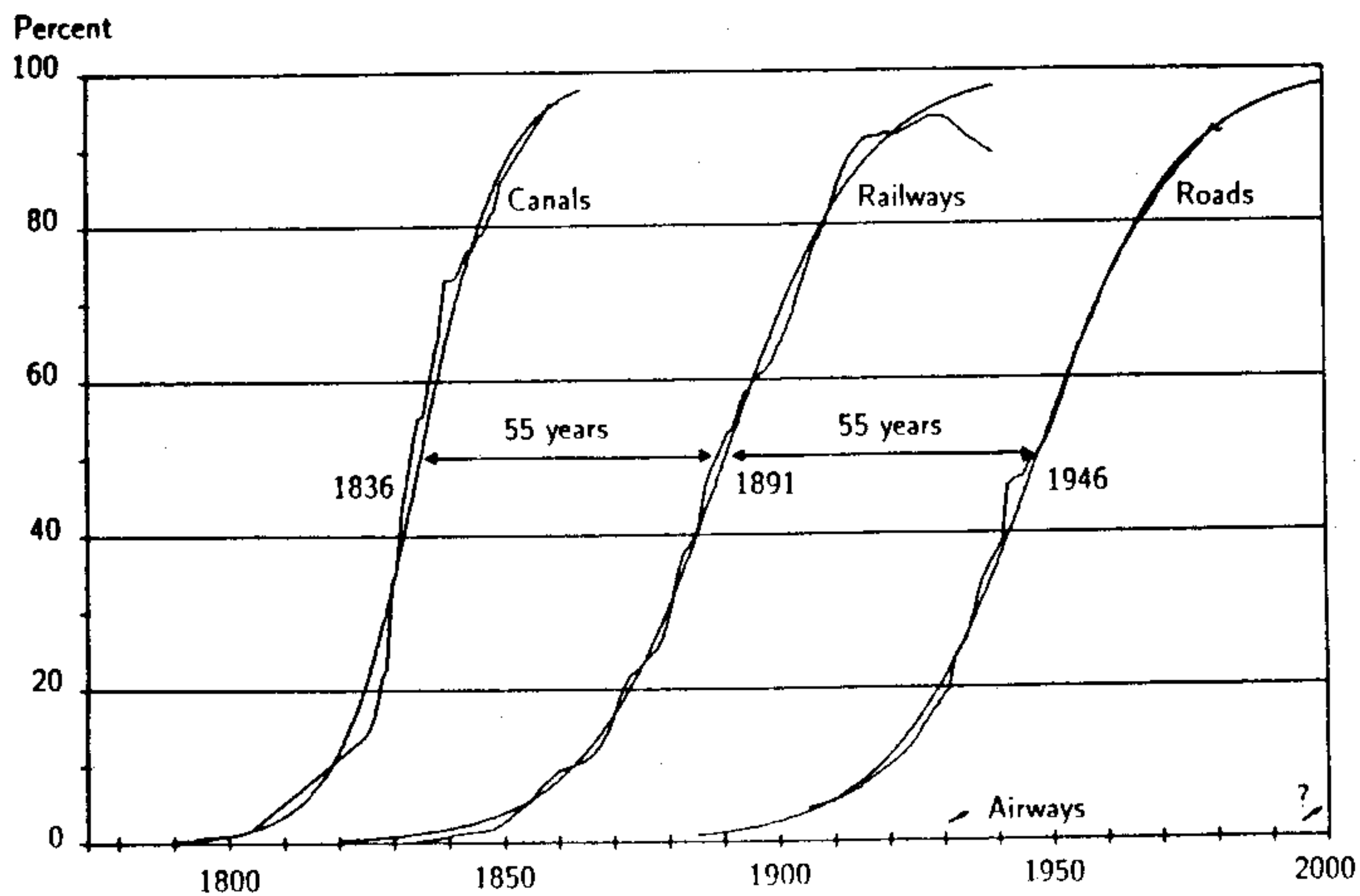
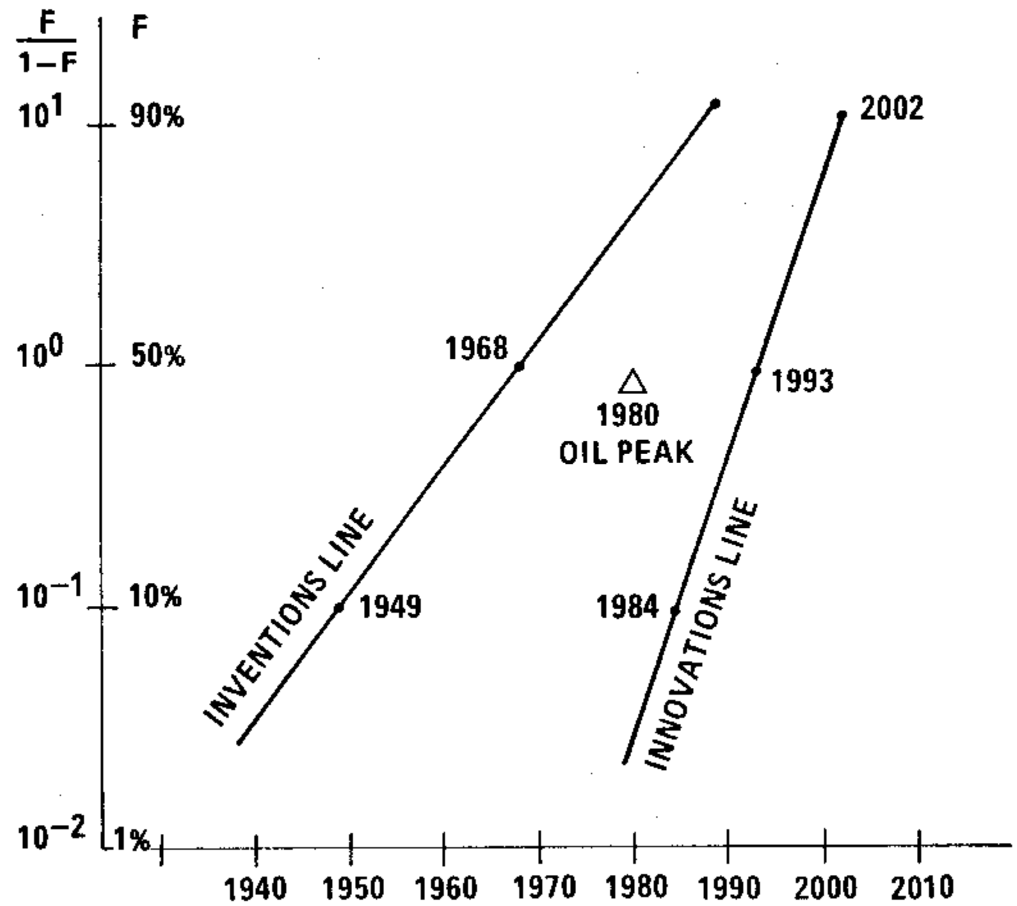

Percent
100
80
60
40
20
0
1800
1850
1900
1950
2000
Canals
Railways
Roads
Airways
?
55 years
55 years
1836
1891
1946

Fig.19.

Coming back to our invention–innovation waves, the last (present) one is reported here with numerical appendages. It may be interesting to know that the centerpoint of our innovation wave is in 1993. So *we are right in the center of the window of opportunity.* It will close in about ten years. These are *basic innovations* in Mensch's definition. Incremental innovations follow different patterns but I have not studied them yet. Inventions seem to be out, almost. This means that the inventions (basic) that will enter the next Kondratiev cycle (starting in 1995) as innovations are already here. The next round will be in 50 years. Inventors (basic) be patient!

Fig.19.



F/1−F
F
10^1
90%
10^0
50%
10^-1
10%
10^-2
1%
1940
1950
1960
1970
1980
1990
2000
2010
INVENTIONS LINE
1949
1968
1980
OIL PEAK
INNOVATIONS LINE
1984
1993
2002

Fig.20.

The type of analysis started with Fig.5 carries a lot of suggestions for the R&D manager as it shows the status of the things in chrystalline clarity. So we keep going showing a few other examples that may stimulate R&D managers into various disciplines. The *vitamin D metabolism* reported here in terms of cumulative number of key publications seems to be exhausted already.

Fig.20.

VITAMIN D METABOLISM (specimen 92) cited core papers

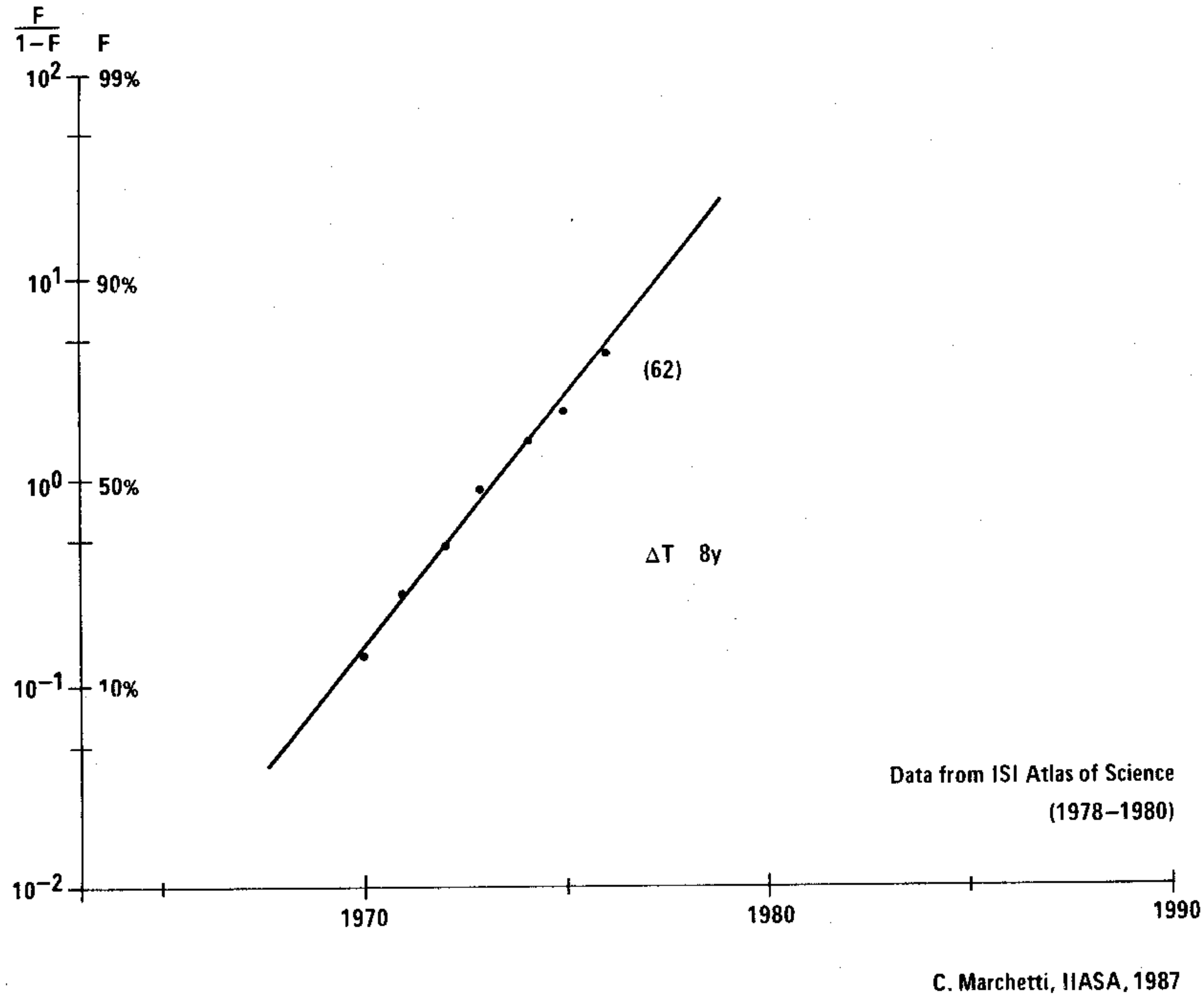


Fig.21–22.

For R&D managers in materials development in view of new technological applications, I report here *Rare Earths Cobalt Magnets*, both in terms of publications (as listed by the Chemical Abstracts) and in terms of patents granted (Chemical Abstracts). For research all the cards seem to be played. One can always start a new run, but a really clever idea is necessary as a seed. From the technological point of view the situation appears still active. One should however take into account that the patents reported here are already granted. The ones in the pipeline will eat a few years ahead.

Fig.21.

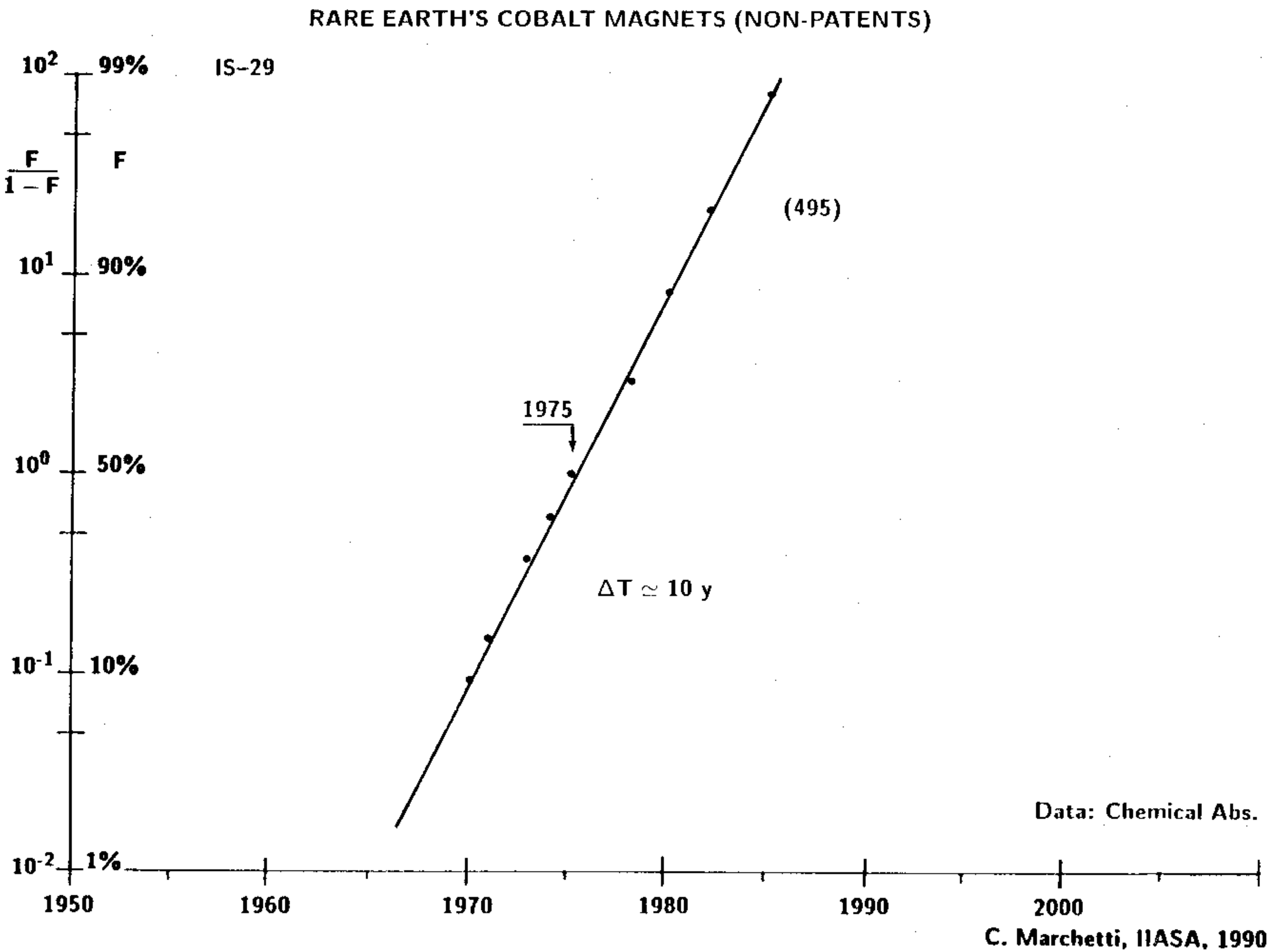

RARE EARTH'S COBALT MAGNETS (NON-PATENTS)
IS-29
10²
99%
F/(1 − F)
F
10¹
90%
10⁰
50%
10⁻¹
10%
10⁻²
1%
1975
(495)
ΔT ≃ 10 y
Data: Chemical Abs.
1950
1960
1970
1980
1990
2000
C. Marchetti, IIASA, 1990

Fig.21–22.

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Fig.22.

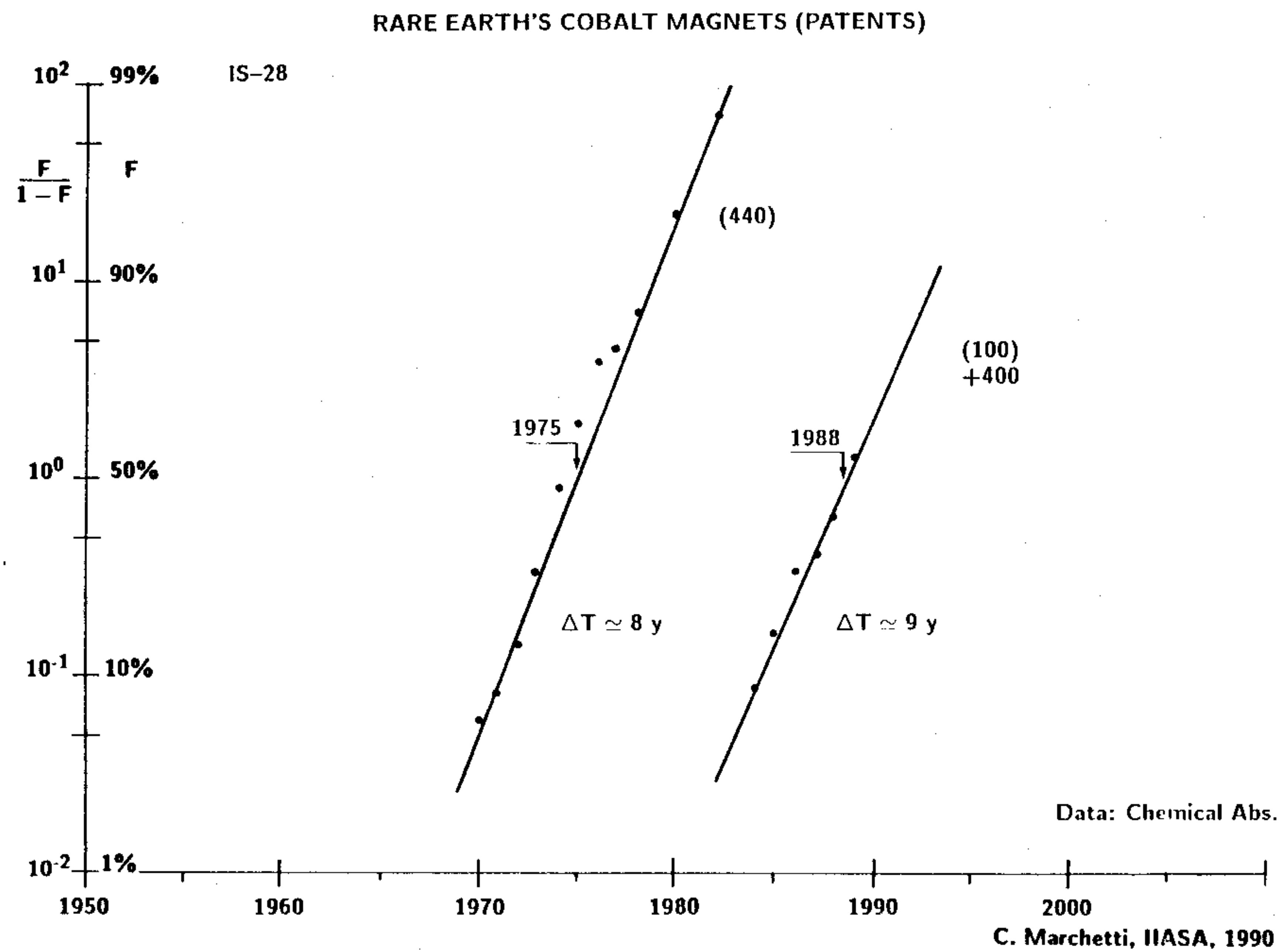
RARE EARTH'S COBALT MAGNETS (PATENTS)
IS–28
$\frac{F}{1-F}$
F
10^2
99%
10^1
90%
10^0
50%
10^{-1}
10%
10^{-2}
1%
(440)
(100)
+400
1975
1988
$\Delta T \simeq 8$ y
$\Delta T \simeq 9$ y
Data: Chemical Abs.
1950
1960
1970
1980
1990
2000
C. Marchetti, IIASA, 1990

Fig.23–24.

I move here from low-volume somehow exotic materials, to a mass-produced one, PVC. It may seem that everything has been said about PVC but the analysis of publications shows something is still in the pipeline. What is unexpected is that *patents* (Fig.24) are only halfway and the long time constant (22 years) tells us that this field has still much unexploited potential.

Fig.23.

PVC – NON-PATENTS

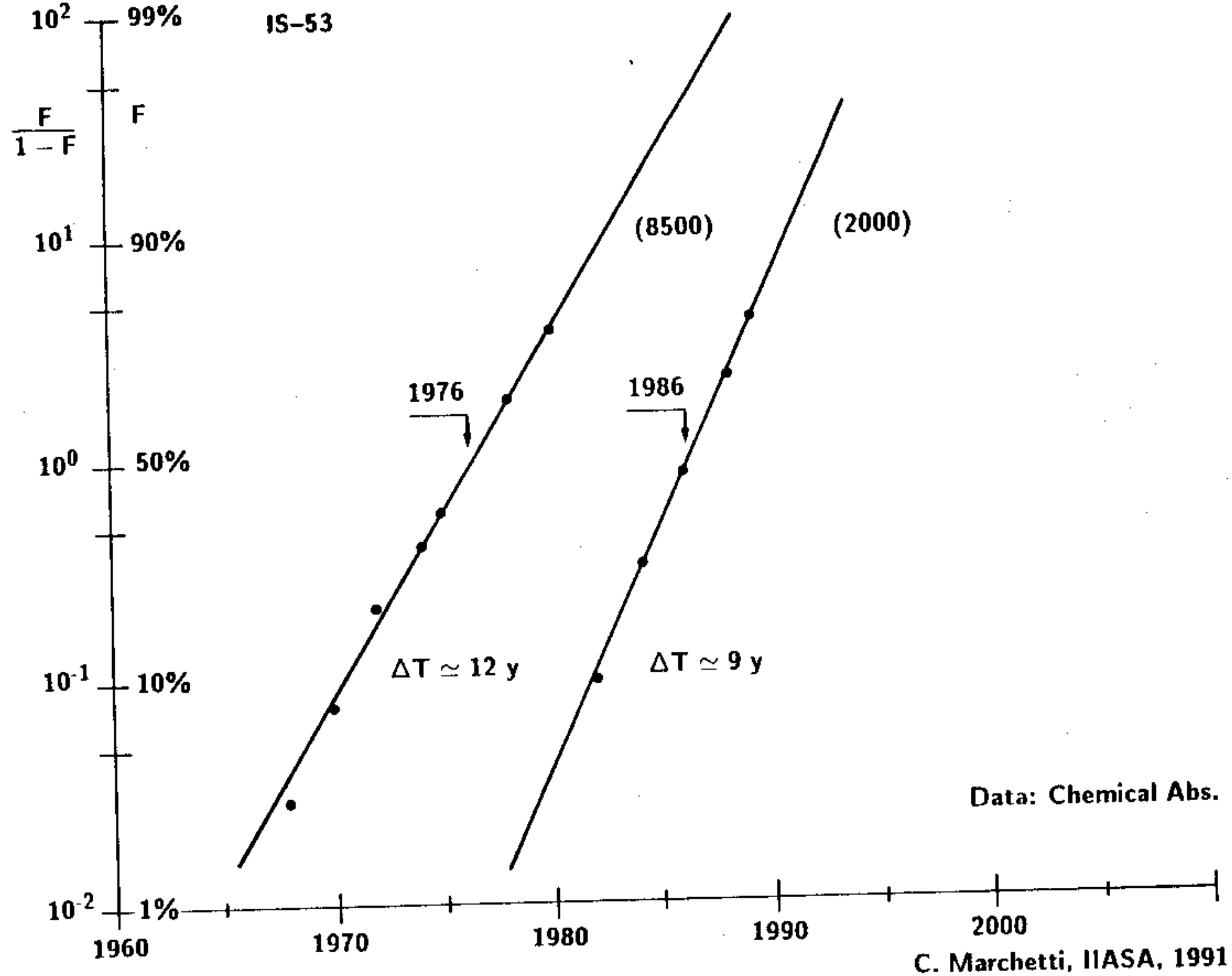

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Fig.24.

PVC – PATENTS

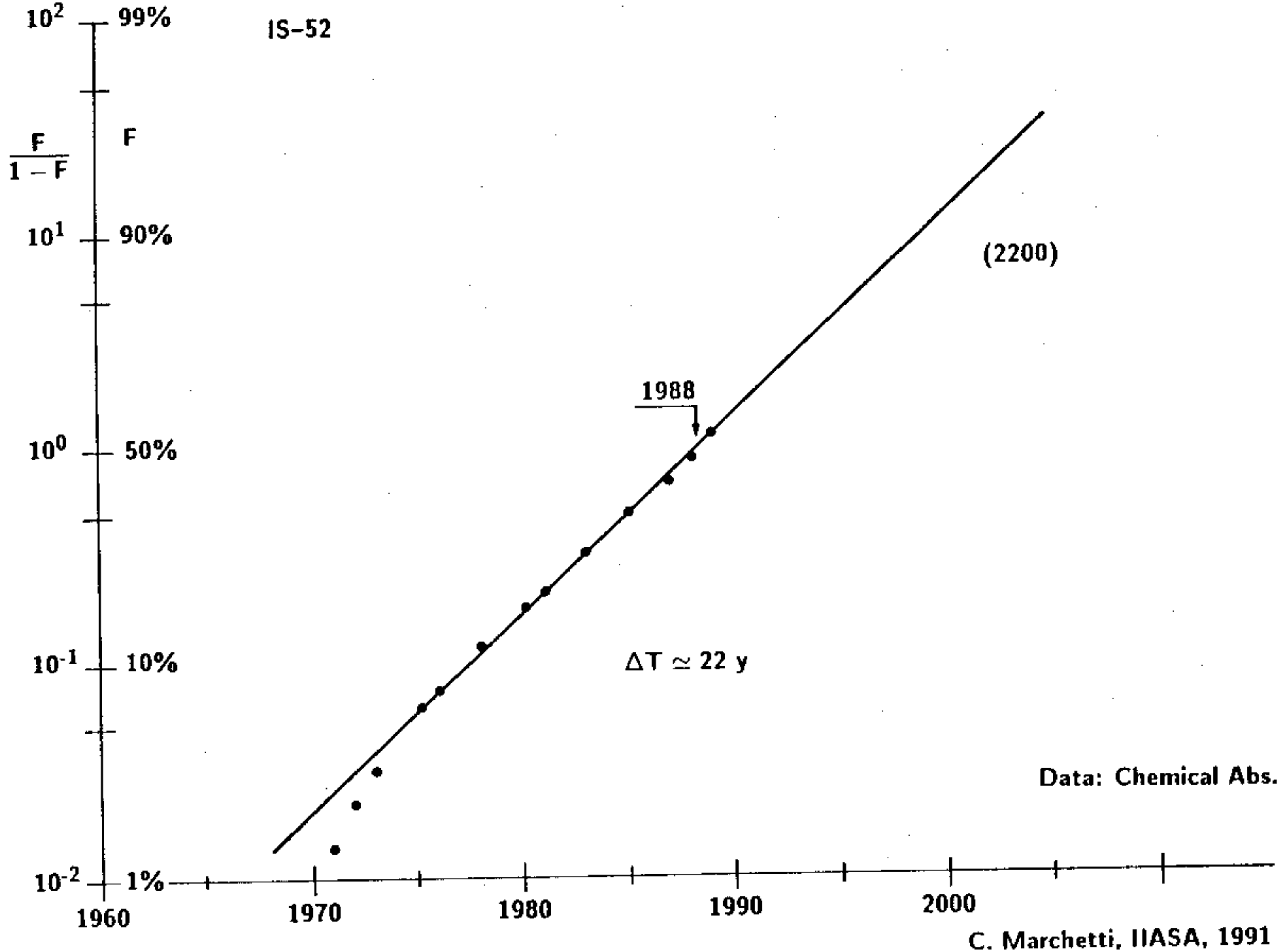

Fig.25.

The comments in the legend of Fig.23–24 may lead to cynical comments. How can one identify how much has *still* to be discovered in a certain area? The fact is the *probability* of discovering is high if there is still much to discover. Because discovery is so precisely organized, the evolution of the rate of discovery in the past permits to calculate the dimensions of the hidden hip (if not of infinite precision, the estimates can be valuable). So I reported here a historical case, that of the discovery of the chemical elements. The post-mortem analysis shows in full the tight regulation of the process. It is due to this (self)regulation that we can implant forecasting procedures.

Fig.25.

DISCOVERY OF CHEMICAL ELEMENTS

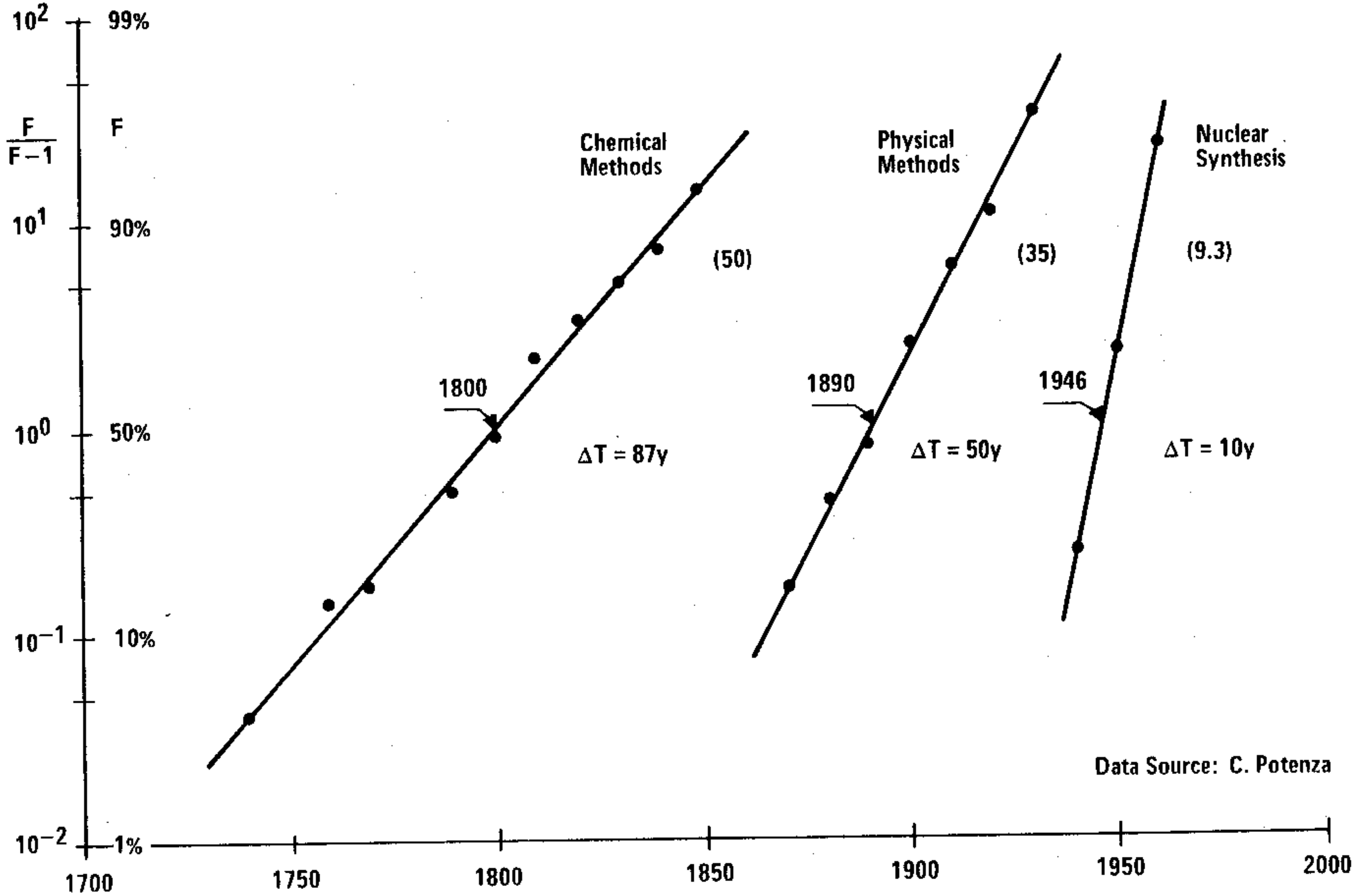

Fig.26–27.

After the methodological insert, let us proceed in the area of large production volume plastics; the penetration of PVC in the USA is shown here. The saturation is linked to the cycle. In Fig.27 the substitution of various materials with plastics, in the construction of pipes, shows a roof of substitutability of 70% (in volumes). Perhaps a search to extend applications (e.g., to high-pressure oil and gas transport) could be an interesting objective for R&D, seen the volumes and the values in the game.

Fig.26.

USA – PVC FOR PIPES ($10^6 m^3$)

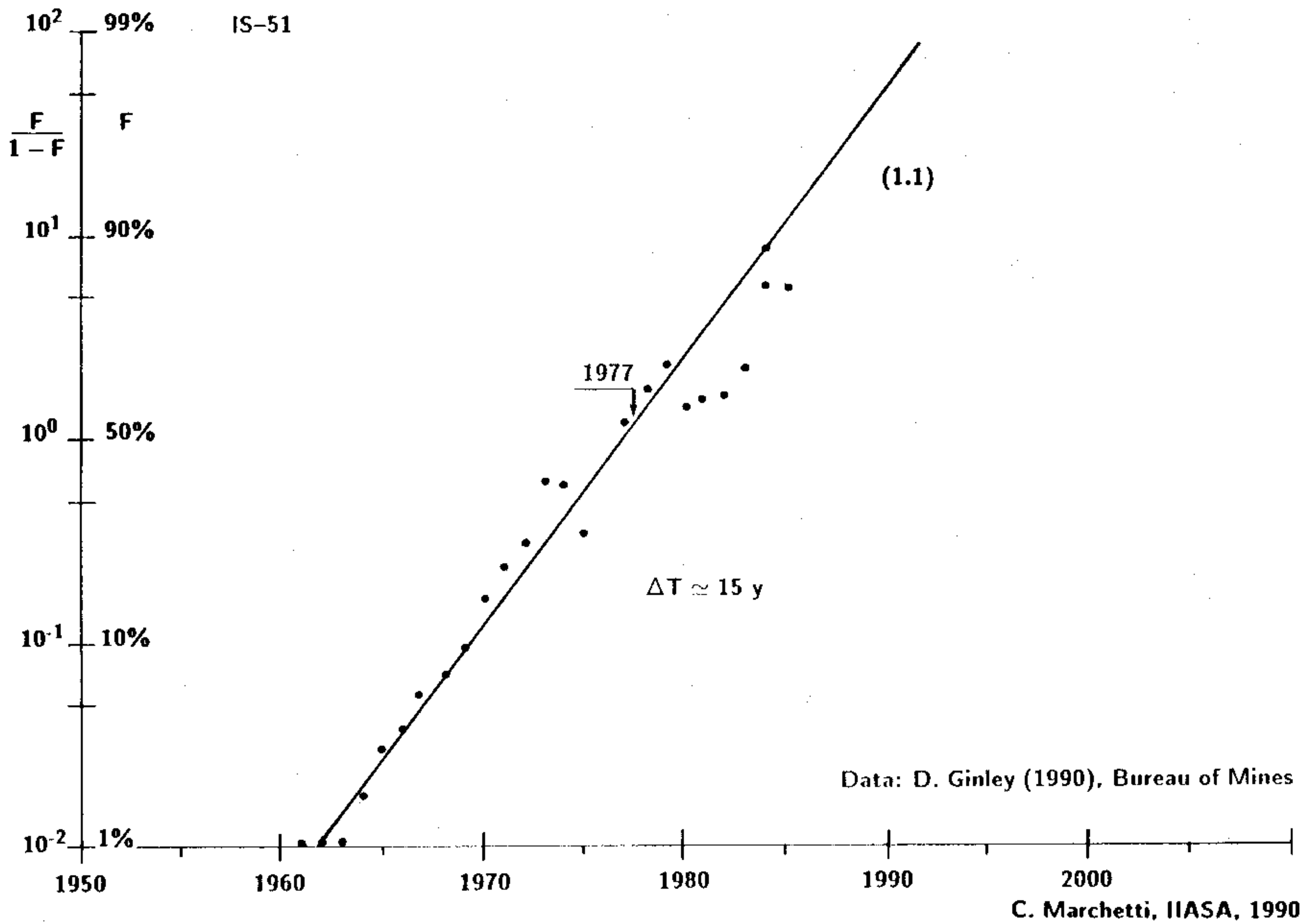

Fig.26–27.

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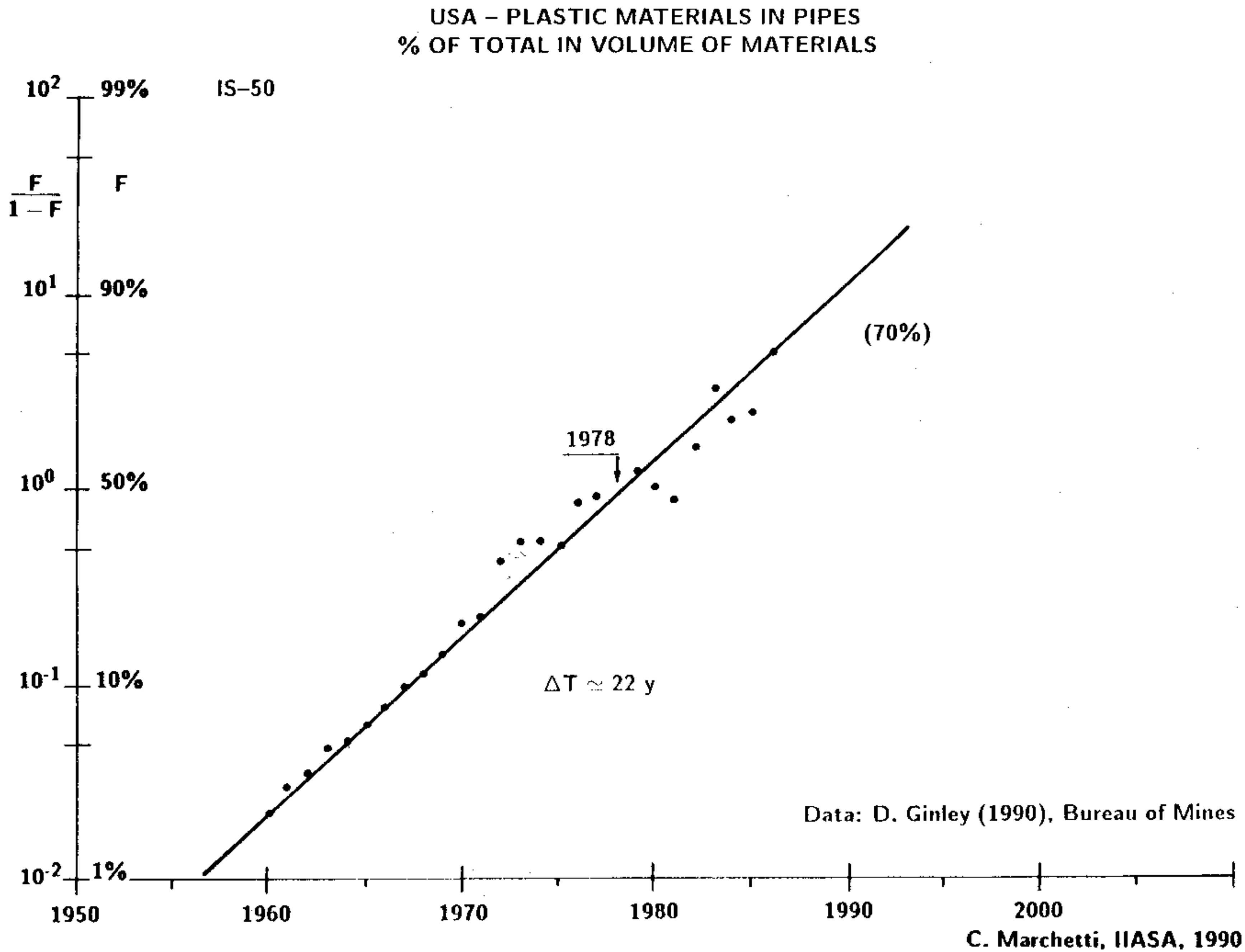
Fig.27.



USA – PLASTIC MATERIALS IN PIPES
% OF TOTAL IN VOLUME OF MATERIALS
IS–50
10^2
99%
$\frac{F}{1-F}$
F
10^1
90%
10^0
50%
10^{-1}
10%
10^{-2}
1%
(70%)
1978
ΔT ≃ 22 y
Data: D. Ginley (1990), Bureau of Mines
1950
1960
1970
1980
1990
2000
C. Marchetti, IIASA, 1990