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ON GEOENGINEERING AND THE CO_2 PROBLEM

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PREFACE

One of the main research lines of the IIASA Energy Program is the analysis of the long term consequences of the use of energy.

Fossil energy leads to the release of very large amounts of CO_2 into the atmosphere which due to sluggy kinetics take a very long time until they are eventually digested in the final sink of the deep ocean. As a consequence, CO_2 accumulates in the atmosphere, and by altering the infrared diffusion it may provoke important changes in the earth's climatic and rain patterns.

In our study we take a positive attitude toward the problem in that we look if it can be solved or reduced by taking proper measures in the way of burning fossil fuels.

This is done in the spirit of geoengineering, which is a kind of "system synthesis" where solutions to global problems are attempted from a global view.

ABSTRACT

The problem of CO_2 control in the atmosphere is tackled by proposing a kind of "fuel cycle" for fossil fuels where CO_2 is partially or totally collected at certain transformation points and properly disposed of.

CO_2 is disposed of by injection into proper sinking thermohaline currents that carry and spread it into the deep ocean that has a very large equilibrium capacity.

The Mediterranean undercurrent entering the Atlantic at Gibraltar has been identified as one such current; it would have sufficient capacity to deal with all CO_2 produced in Europe even in the year 2100.

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INTRODUCTION

The problem of climatological effects of CO_2 has recently attracted much attention, but the related question of how much fossil fuel we can still burn without burning our fingers is yet open. It may turn out that burning fossils "à gogo" will have no really important consequences at least for our generation; yet reports on the subject following the spirit of the time perhaps, tend to be more and more pessimistic.

The first order effects are thought to be caused by the intense absorption bands of this gas in the infrared window of the atmosphere, i.e. in the region between approximately 8μ and 12μ. Calculations show that the isotropic scattering and absorption-re-emission of infrared radiation by CO_2 molecules in the atmosphere reduce the diffusiveness of infrared radiation, consequently producing a so-called greenhouse effect.

As water is competing with CO_2 in the same window, the effect will be larger where water concentration is lowest; this is so in the anticyclonic areas over the deserts, for example, and especially over the poles where due to the very low temperatures the water content is at a minimum. This can produce a second order effect, namely a decreased horizontal lapse rate between the poles and the equator, which would directly influence the circulation cells and the precipitation regime.

A third order effect may come from the increased photosynthetic rate of plants for which atmospheric CO_2 tends to be a limiting factor. This increase may induce a higher level of plant coverage, thus tendentially decreasing the earth's albedo and consequently working in much the same way as the greenhouse effect but with a concentrated influence upon temperate and wet tropical zones.

An increase in temperature in the polar regions would bring about a similar positive feedback as it would induce a reduction in the snow cover and floating ice coverage, thus reducing the albedo and increasing the energy input.

These effects have been analyzed mainly at the level of total energy balance, with some attempts at quantifying latitudinal effects, but to my knowledge there has been none to introduce the albedo-vegetation feedback. For these reasons, and the still rudimentary state of the models, the results given in the literature should be taken at their face value when we try to derive general consequences from them. The personal opinion of people working in the area, however, is that a refinement of these results will probably force us to draw a bleaker picture.

As the CO_2 problem could, in the short and medium term, impose substantial restrictions upon the burning of fossil fuels, any energy strategy that is framed in present day technology may be strongly conditioned by them. So I decided to see if a geo-engineering approach may not provide some conceptual line for solving the problem or at least minimizing its consequences. This operation is done in the spirit that technology basically should try to open new options or at least keep old options open.

Now, if we analyze the process of burning fuels with an eye on the fate of carbon, we see that:

We start from a very concentrated form of carbon;
We go to a dilution of carbon of one or two orders of magnitude in the combustion gases;
We dilute it again perhaps by five or six orders of magnitude by dispersing these gases into the atmosphere;
We have to wait for this very dilute stuff to diffuse through the surface of the sea into the thin mixed upper layer of the ocean;
We have to wait for the mixed upper layer of the ocean to mix with the bulk of the semidormant oceanic mass.

The capacity of the final sink, the oceanic mass, is very large indeed and we may safely assume that once the dissolved CO_2 is completely equilibrated its level in today's atmosphere would be inperceptibly different from the "historical" one of 290ppm. The problem appears, at least for the next 100 or 200 years, to be essentially a problem of global kinetics: so kinetics is the place where the cure has to be applied.

The obvious line of attack would be to avoid the whole chain of dilutions and interfaces and to put CO_2 directly into the deep ocean. This may seem more easily said than done, but as I will show later the basis for a technologically and economically feasible operation does exist.

We will logically divide the operation into three steps: the collection of CO_2, its transportation and disposal.

CO_2 COLLECTION

This is not the place to think of each consumer filling his own little balloons with CO_2 to be processed by his municipality. The problem has to be tackled upstream.

Coal: Today roughly 80% of coal is used in large installations such as power stations and blast furnaces. The combustion product in the first case is CO_2, in the second it is a mixture of CO_2 and CO. In both cases one of the numerous (a dozen) processes of stripping CO_2 from other gases (e.g. to strip CO_2 from steam-reformed methane in order to purify hydrogen) which are currently used in industry could be employed. They are usually based on a scrubber where CO_2 is first dissolved in water or in other solvents weakly binding it and is later liberated by heating or pressure changes.

In power stations this process could be associated with SO_2 scrubbing so that only nitrogen is finally released to the atmosphere. The final purification level can be adjusted in a tradeoff with cost. If coal is used to make synthetic natural gas, given today's efficiencies about two thirds of the carbon appear in the CO_2 already collected by the process itself.

Oil: Practically 100% of all crude oil is processed today through the refinery. As the hydrogen-carbon ratio is generally increased in the refining, a certain fraction of the carbon (20%?) appears as CO_2, most of which has already been collected in the process. New processes have been developed recently to produce SNG from medium-light oil fractions at a high energy efficiency (~95%). Roughly 50% of the carbon appears as already collected CO_2. Similar processes using crude oil as feed are at the prototype stage. The collected CO_2 is of the same order.

With these technological facts in mind, let us look at my analysis of world trends in energy demand, which indicates a strong movement toward gas for fixed installations in the next 50 years [1]. This means that if as a first step the management of coal and oil were slightly adjusted, probably as much as 50% of the carbon could be removed at marginal costs in the form of concentrated CO_2 that would then be available for further processing.

The following step would be more drastic and presumably more costly. It calls for a transformation of the primary fuel into a final fuel at a point where it carries no more carbon. This fuel can be H_2, NH_3 or N_2H_4. The problems and merits of an energy system based on hydrogen as a fuel has been analyzed and widely discussed during the last five years, especially in relation to a widespread use of nuclear reactors as primary energy sources. I assume that it is a feasible and highly advantageous proposition which will probably be the inevitable conclusion of two hundred years of evolution of the energy system.

If hydrogen will be the final energy vector, all CO_2 can be collected at the transformation point where hydrogen is generated, probably using a mix of fossil and nuclear fuels.

CO_2 TRANSPORTATION

CO_2 can be easily compressed to a liquid of 60-70atm at room temperature. This liquid has a low viscosity and pumps like water. It can be transported in pipelines that are essentially the same as those for methane. The high pressures needed to carry CO_2 in a liquid form, even if it is moderately chilled, make the use of normal oil tankers improbable. But the problem has not been examined in detail and simple tricks may be discovered to do that. Solid CO_2, for example, can be piled on barges.

For the sake of our discussion I will assume that only liquid CO_2 is carried overland in pipelines. I am also confident that the cost of transporting it anywhere will finally be lower than the cost of "forward" fuel transportation which could be taken as a reference.

CO_2 DISPOSAL

This could be done in the form of a permanent underground storage, e.g. by using exhausted gas fields. This possible storage of liquid CO_2 at pressures lower than 100atm guarantees a larger storage capacity than for the original methane, although the solubility of CO_2 in water and the solubilization of carbonate rocks do not guarantee a similar stability over time. The same could be said for exhausted oil fields and other types of natural or artificial cavities.

I did not go into the details of this system on the grounds that the capacity of natural structures which is available at reasonable cost may be insufficient. The question, however, certainly merits a second thought.

As said before, the system I was looking for is one that shortcuts the atmospheric link, going directly to the deep ocean. The disposal method should also shortcut the very slow mixing of oceanic waters and should consequently avoid dumping over restricted areas. The solution I find most promising is what I call the Gigamixer. In the Mediterranean, the rate of evaporation largely exceeds the inflow of water from rivers and rain, thus leading to an increase in salinity and to a net inflow from the Atlantic. At Gibraltar, at the bottom of the Strait, a current of dense and warm (13°) Mediterranean water flows into the Atlantic, being at the same time substituted by slightly larger amounts of lighter and colder Atlantic water. The throughput of each current is of about $\sim 2 \cdot 10^6 m^3/sec$. The outgoing water has a density quite different from that of the Atlantic and it sinks gently, like a huge and slow waterfall, moving westwards and finally spreading at an equilibrium buoyancy level of ~1 500m. The spread is flat and wide and covers practically all the Atlantic. Mediterranean water can be detected also in the Indian Ocean. The phenomenon had been extensively studied in the thirties by G. Wüst (see for example Ref. [2]), in the fifties by A. Defant [3], and was recently modelled by H. Sendner [2]. This middle water then diffuses up and down (mainly up) and part of it is caught by the sinking currents in the Weddell and Norwegian seas. It will presumably not see the light before a good thousand years, and by then will be thoroughly mixed with the rest.

Assuming that our CO_2 is injected in the neighborhood of the Strait of Gibraltar at the proper pressure, depth and amount, the current would spread and mix it with the core of the oceanic middle waters.

How could this mixer match the input? What the permissible CO_2 concentration can be is an open question. One can find values in the literature which are meant to be safe because they do not interfere with the shell-forming capacity of molluscs and other creatures precipitating $CaCO_3$ for their private use. According to W.S. Broecker [4], 1‰ can be quite acceptable. Leaving the question of the maximum allowable level to further discussion, let us define some links between this concentration and the energy use of CO_2. The amount of industrial CO_2 produced in the world today is, according to C.D. Keeling [5], approximately 10^{10} tons per year. The amount of water passing through the Strait of Gibraltar at 2MT/sec is about 10^{14} tons per year. The ratio of 10^{-4} is ten times lower than the safety limit. Thus the scale of the sink seems to match well with that of the source.

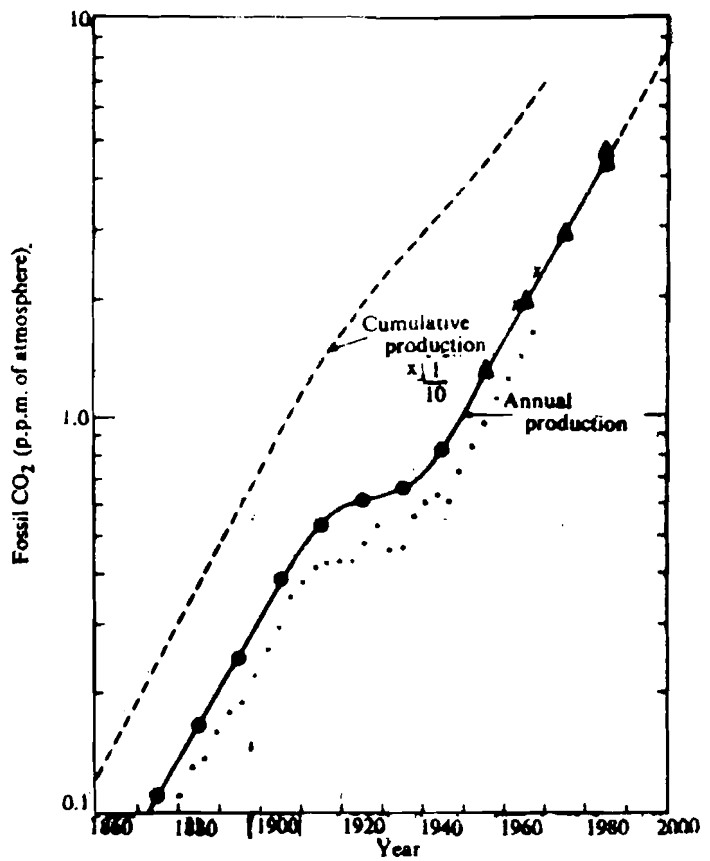
The following question is of a logistic character. Should all the CO_2 be sunk there? The first thing to do obviously is to look for other places of analogous properties that are possibly located near energy consumption points. The Red Sea currents in Bab el Mandeb closely simulate those of Gibraltar although in a lower scale. The poles have gigantic sinking regions, those in the Weddell Sea and the Norwegian Sea produce ocean bottom water. The three sites do not conform with the second condition of proximity to energy consumption points. The search is open, however.

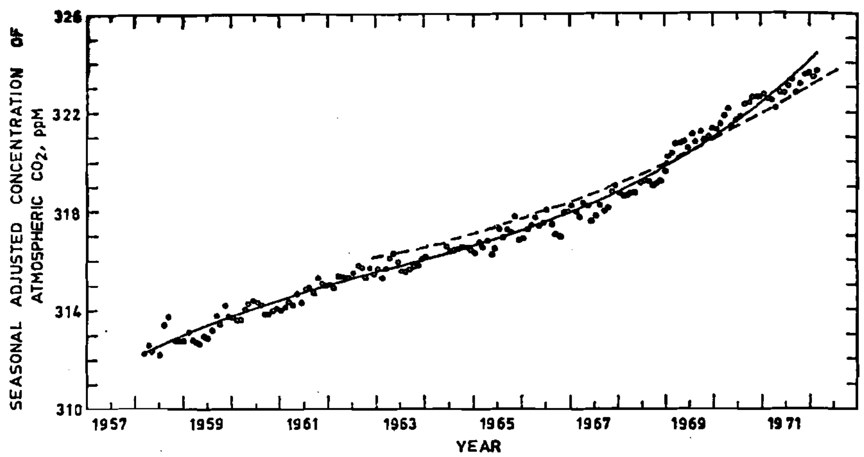
Another much more drastic solution has been proposed by W.D. Nordhaus [6]. The CO_2 phase diagram shows a small region for temperatures between $0^{\circ}C$ and $10^{\circ}C$, where the density is somehow higher than 1, e.g. 1.05. The corresponding pressures are in the range of 150 to 300atm. This means that after injection with a long pipe into the deep sea, the liquid CO_2 would come out to be denser than sea water and would fall down to the bottom. There it would make a "lake" of LCO_2 that is somewhat analogous to the hot brine lakes at the bottom of the Red Sea. If the depression where the LCO_2 collects is narrow and deep, this form of containment may well have a half life of centuries, as only the slowly moving bottom currents carry away the CO_2 that is diffused into the water covering the LCO_2 pool. The analysis of the behavior of the Red Sea brine pools and of others may provide a trace for evaluating the behavior of this kind of storage.

CONCLUSION

The problem of the atmospheric CO_2 level as a consequence of fuel burning appears much eased if equilibrium conditions with the whole oceanic mass are taken into consideration.

In order to shortcut the sluggish kinetics of that equilibrium, a CO_2 management system is proposed where CO_2 is collected at proper fuel transformation points and finally injected into the deep seas taking advantage of natural thermohaline circulations. A rough evaluation indicates a cost to the consumer of 10% of the fuel value for a recovery of 50% of the CO_2 and 20% costs for a recovery of 90%. These figures should be supported by the detailed design of such a system for a sufficiently large area, e.g. for Europe.





Figures 1a and 1b. CO_2 production and accumulation in the atmosphere--historical trends.

Figure 1a shows the production of fossil CO_2 since the 1870's (Source: Ref. [7]); the solid circles are the estimates of R. Revelle and H.E. Suess (1957) extended to 1890 by OECD estimates, the dots are estimates of Keeling (1973).

Figure 1b illustrates changes of the CO_2 content of the atmosphere 1957 to 1972 (smoothed values) as given by C.A. Ekdahl and C.D. Keeling (1973) (Source: Ref. [8]), data points are seasonally adjusted, and solid line (smoothed curve) by B. Bolin and W. Bischof (1970), including unpublished data from the recent years (dashed line, smoothed curve).

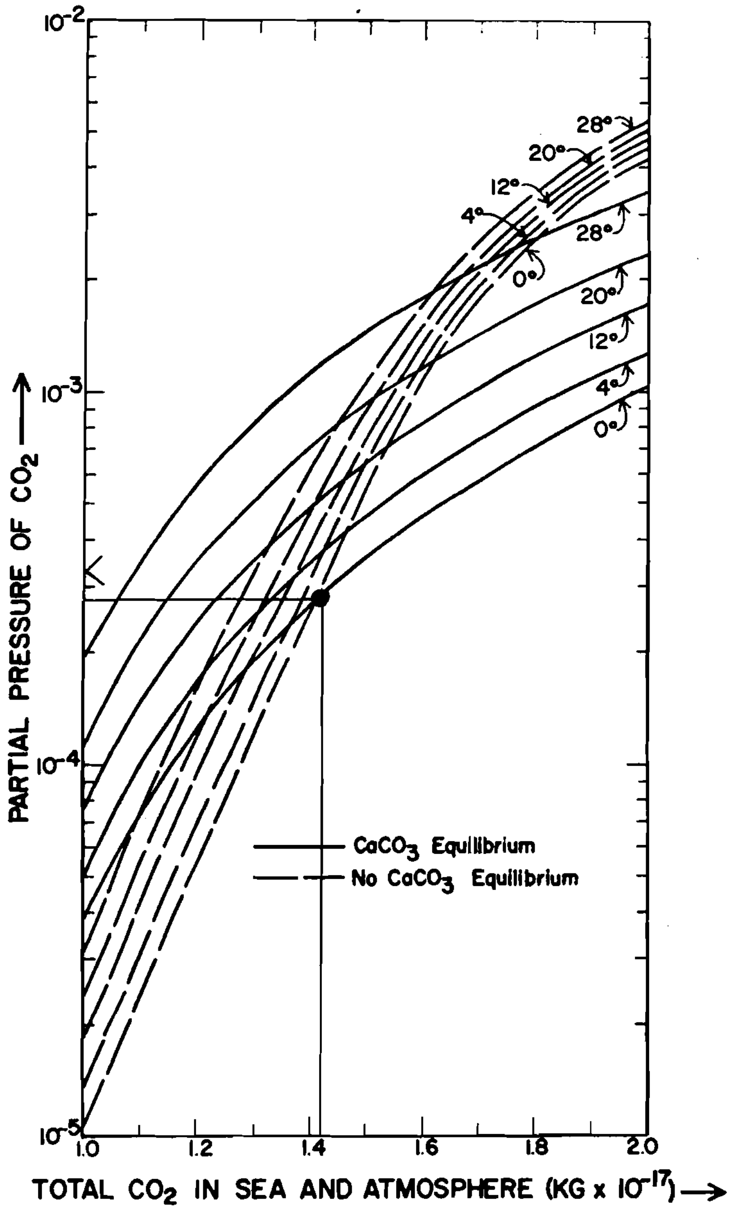


Figure 2. Equilibrium distribution of CO_2 between the atmosphere and the ocean at various ocean temperatures. The present addition of "fossil CO_2" to the system is about 10^{13}kg/year. < indicates today's level (non-equilibrium) of CO_2 in the atmosphere. The total CO_2 amount in the ocean and atmosphere is 1.42 10^{17}kg. (Source: G.N. Plass (1972) Ref. [9])

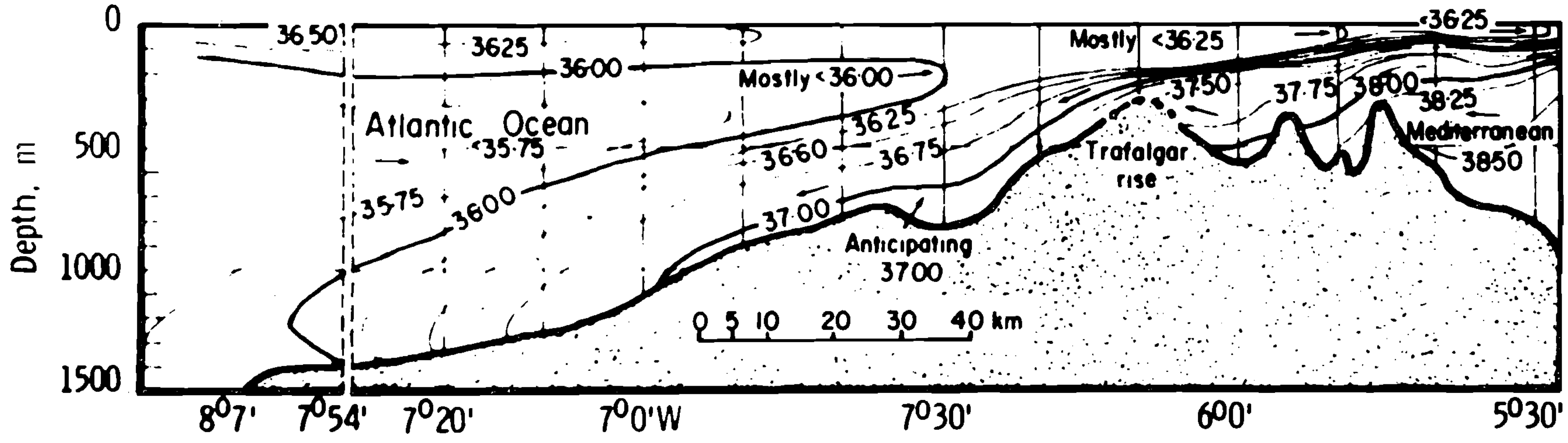
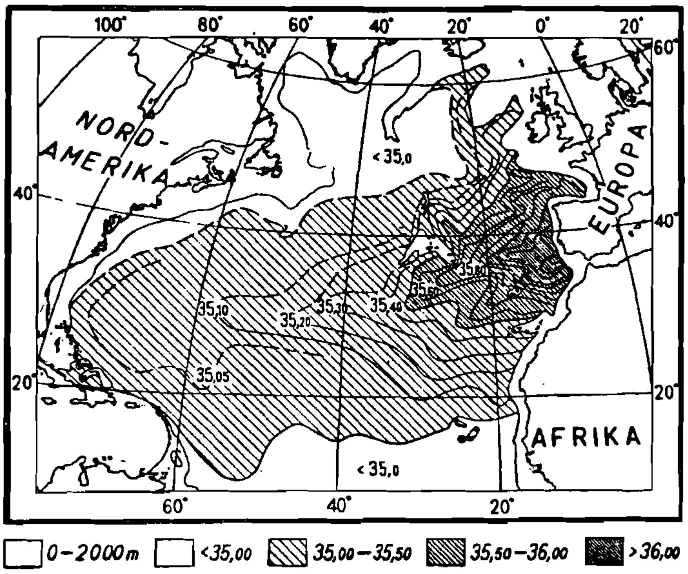
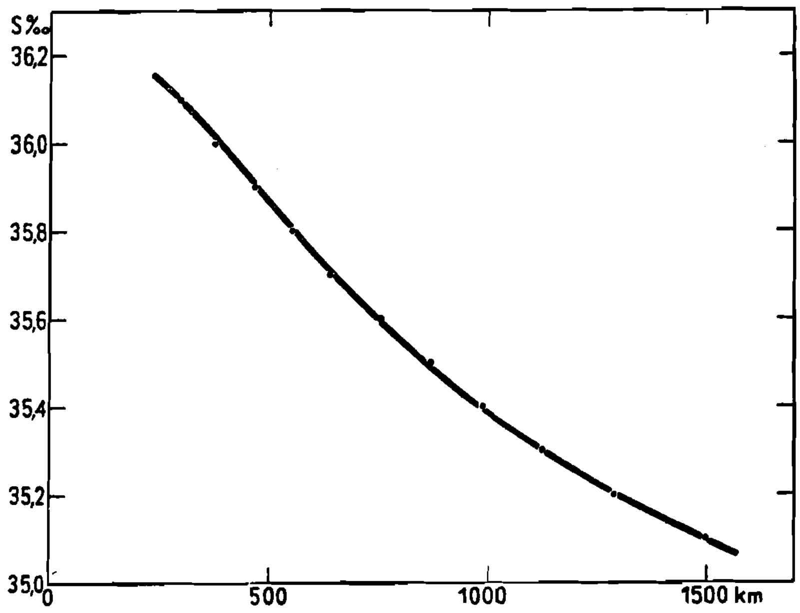


Figure 3. Salinity profile through the Straits of Gibraltar in spring-summer from A. Defant (1961) (Source: Ref. [3])





Figures 4a and 4b. Mediterranean water progressing into the Atlantic (Source: Ref. [2]). The salinity data in Figure 4a are from G. Wüst (1935). Figure 4b fits Wüst's data using H. Sendner's diffusion theory (1958).

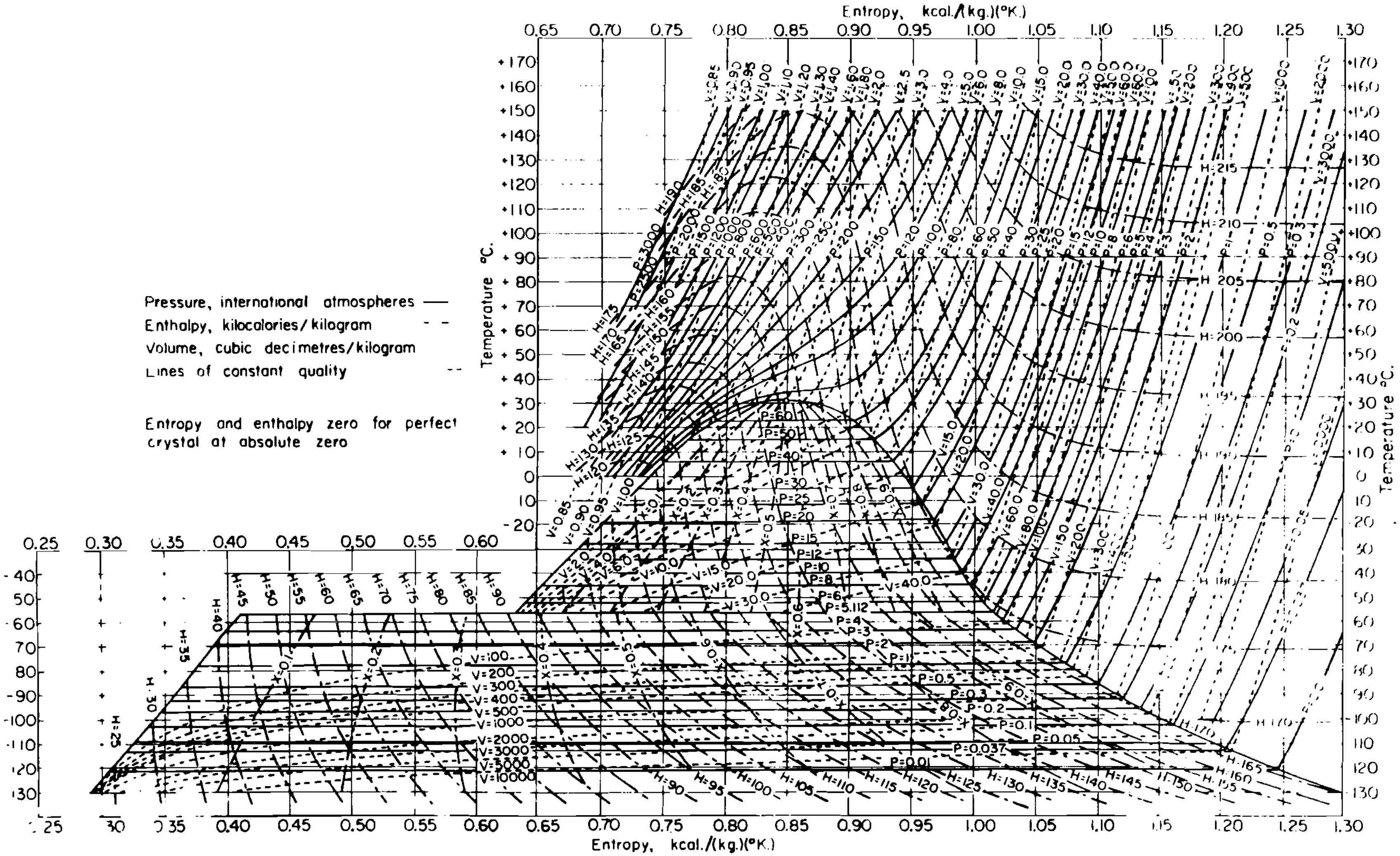


Figure 5. Temperature-entropy diagram for carbon dioxide (Source: F. Din (1956) Ref. [10])

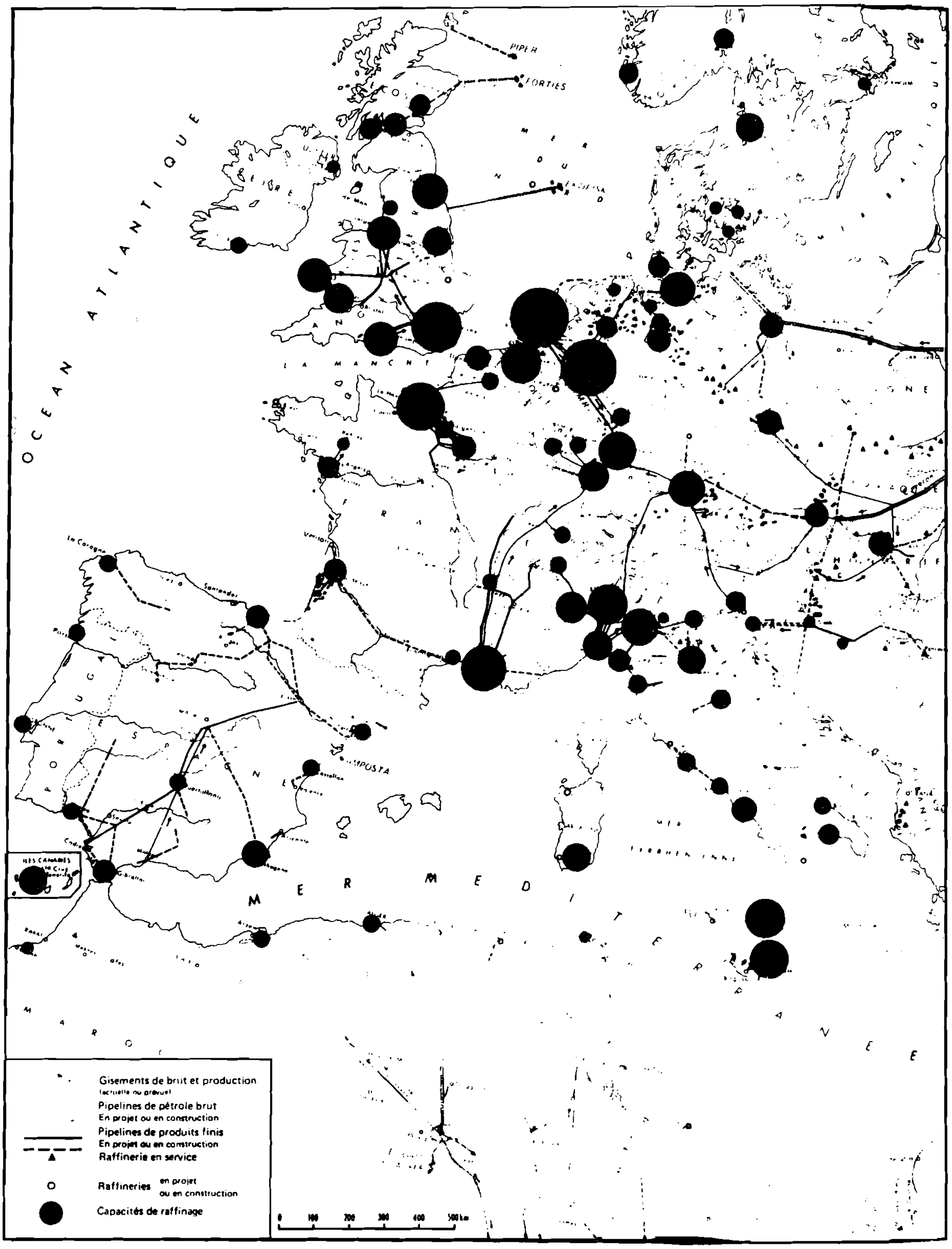


Figure 6. Oil refineries in Europe and oil pipelines.
(Source: Ref. [11])

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