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A Non-Linear Eight Level Tandem Model to Calculate the Future CO_2 and C-14-Burden to the Atmosphere

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PREFACE

Risks have emerged as a major constraint to the introduction and development of technological systems. The work of the Joint IAEA/IIASA Research Project (IAEA = International Atomic Energy Agency) is directed toward gaining an improved understanding of how societies judge the acceptability of new technologies and how objective information on risks, and the anticipated responses to them, may be considered in decision-making. A conceptual framework is being used for risk assessment studies which includes in addition to the consideration of physical risks, the perception of risk situations and the resulting psychological and sociological levels of risk.

This paper deals with the identification of physical risks. A model to calculate the future CO_2-burden to the atmosphere is presented and is applied to various energy supply strategies.

ABSTRACT

The combustion of fossil fuels leads to carbon dioxide emissions which may significantly disturb the global carbon cycle. This leads to a potential risk on account of the influence on the radiation balance of the earth. An eight-level tandem-model, based upon non-linear differential equations, was developed to simulate the possible effects of alternative strategies which might be used to meet future energy demands.

This tandem-model also calculates C-14-flows, therefore making it possible to simulate the Suess-effect and the influence of C-14-emissions from the nuclear power fuel cycle. The radiation exposure due to C-14 does not depend upon its absolute atmospheric concentration, but upon the C-12/C-14-isotope ratio; therefore, two effects are counteracting. The C-14-free CO_2-emissions of fossil fuel consumption dilute the relative concentration and lead to a decrease in radiation exposure.

Even based upon optimistic assumptions for the introduction of nuclear energy, an average global temperature increase of 1.8 ^{o}C is predicted by the end of the next century. The radiation dose due to C-14 would increase 2.4 mrem/yr above natural level. Assuming energy needs are met solely from fossil fuel, an average temperature increase of ~ 9 ^{o}C is estimated.

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I. Introduction

Traditionally the side-effects of new technologies have been determined through a process of trial and error, the primary criteria for application being the direct technical or economic aspects. However, as technical systems have become larger their side-effects have become correspondingly larger, sometimes being global in character. When these man-made disturbances are in the same range as natural processes then there is little hope that nature can compensate for them. This is the case for some common metals, (e.g., lead, iron, copper) where the mining rates are more than ten times as high as natural material flow rates due to the wash-out by rivers. The natural flow rate of carbon by net-assimilitation of plants is still about 15 times as high as the emissions from fossil fuel combustion, but will soon be of the same order of magnitude.

Thus, potentially important side-effects of technology must now be taken into account prior to application. This "identification of the side-effects of a decision and the subsequent estimation of their probabilities and the magnitude of the associated consequences" has been defined as risk estimation which is the first step in the complex process of risk assessment. The second step then is risk evaluation, which is the "process of determining the meaning or value of the estimated risks to those affected, that is

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individual, group and society". A conceptual framework for risk assessment studies and preliminary research results, have been reported by Otway and Pahner (1).

In the following paper, a simulation method based on non-linear differential equations is applied to estimate some side-effects of various global energy supply strategies.* The calculated risks with regard to carbon dioxide are of less public concern than would be expected considering their magnitude. One reason seems to be that it is very difficult for people to realise that a process which man has used for decades or centuries may actually be causing a high risk. This is another example of the necessity of better understanding the social and psychological factors which determine the ultimate acceptance of technological risks by the public.

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*The results of these calculations were partly published in the report series of the Nuclear Research Centre Juelich, FRG (See Reference 3).

II. Model-Simulation and Prognosis

By building a model the characteristics of the real system which influence the behaviour under consideration are translated into a set of mathematical equations, thus rendering the possibility of conducting experiments which, upon the real system, would either be too expensive or not be possible at all. To be sure that conclusions can be drawn out of the model calculations, it has to be proven that the model behaviour represents the behaviour of the real system. An important part of the verification of a model is the correct simulation of the past with regard to the development of exogeneous variables. Furthermore, it is necessary that special conditions such as stationary equilibrium or special attributes, e.g. stability under certain circumstances, must be accurately simulated.

The basic behaviour of a system is analysed, as was done with good results by application to technical systems, by means of frequency analysis or simulation of Dirac or step functions. Therefore basic shapes of exogeneous variables are used as input functions to the model, the results of which give information on phase and amplitude relations of system elements. This phase of building a model provides the possibility to test parameters and table-functions, to complete the structure of the model or to disaggregate variables. The analysis of the system behaviour and the verification of the model are parallel steps with feed-back mechanisms. The growth or decrease of variables, minima or maxima must have logical explanations. The sensitivity of the model has to be tested with regard to the whole time-span under consideration. Therefore prognosis of the development of the exogeneous variables are used and parameters, constants, table-functions or initial values are changed according to their reliability.

After thus defining the confidential area of the model, the consequences of various possible future developments can be calculated, and stategies for improving them can be derived, in a prognosis under certain conditions, as tools for decision-making processes. Beyond such an analysis of the future, the most probable developement can be taken as a prognosis on the behaviour of the system.

The classification of a model depends on how well the objectives are met. For many problems an accurate analysis of the principle behaviour of the system may be more important than a good prognosis. This is illustrated by Fig.1 which gives the time-dependent magnitude of a systems variable which was approximated by two models. Model 1 gives a better prognosis of the reality because the error, the averaged squared difference, is smaller but no description is given of the sinus-shaped behaviour which is clearly simulated by model 2, even though frequency and amplitude are not exactly displayed.

III. The Greenhouse Effect

In the following, a simulation method using non-linear differential equations is applied to the global carbon cycle which is of great interest because the CO_2-emissions could turn out to be the limiting factor for the energy production by fossile fuels.

The energy needs of life are naturally provided by decoupling solar energy from the radiation balance of the earth. The process of photosynthesis converts solar radiation to chemical energy which then is transported through the carbon cycle of the earth and is released where energy is needed by decomposing the organic matter. Thus all disturbances of this system have to be watched very carefully. But the toxic limit for plants is beyond a concentration of about five times the normal CO_2-concentration of the atmosphere. Below these values an increase in the concentration stimulates the assimiliation rates of plants, thus having the effect of a good fertilizer. The danger of an increasing atmospheric CO_2-concentration is given by its influence on the radiation balance of the earth.

The average albedo of the earth (including clouds, surface of land and water and the atmosphere) is about 29%. This would lead to a theoretically derived average temperature of 254K. Considering the earth as a black body (albedo 0%) leads to an equilibrium temperature of 277K. This is 34°C and 11°C respectively less than the average real temperature of about 288K (15°C). The reason for the higher real temperature is given by the "greenhouse effect" of the atmosphere, partly caused by H_2O and CO_2. As CO_2 does not absorb the high frequency spectrum of the sunlight, but absorbs the infrared radiation of the earth surface, an increase in its concentration would lead to an increase in temperature. Since 1896, where Arrhenius calculated a temperature increase of 9°C according to a 200% increase, many computations of the CO_2-effect have been performed. A survey of these calculations is given in (3). The most recent calculations depend on a one-dimensional model developed by Manabe and Wetherald in 1966, resulting in a temperature increase of 2.4°C due to a doubling of atmospheric concentration with regard to average cloudiness and constant relative humidity (4,5,6). In the following calculation this value is assumed and will be discussed in greater detail in 6.1.

IV. The CO_2-Emissions

4.1 The Specific Emission Factors

By the combustion of fossil fuels, the solar energy, which was fixed by photosynthesis some hundred million years ago, and was stored as organic carbon compounds, is released. In Table 1 the specific emissions of these fuels, and in addition those of methane, are given, as can be calculated by heating power and carbon content. These are given in the first two columns.

For the sake of comparison, the last column gives a specific emission index which was normalized to 100 as for the emission of natural gas. As can be easily seen, the combustion of lignite has an 80% higher emission factor than natural gas. The use of methane would lead to specific emissions which are 13% less than those of natural gas. But if the emission of the coal gasification is considered, the specific CO_2-emissions of the autothermal (combustion of coal) gasification are higher than by combustion of coal. The allothermal (external heat source) gasification by means of high temperature reactors will have specific emissions somewhat higher than the combustion of bituminous coal. These calculations were performed with regard to the available hydrogen.

4.2 The Emissions of the Past

With regard to the specific CO_2-emissions given in Table 1 the utilization rates of fossil fuels lead to the CO_2-emissions of the past. Figure 2 gives the total emissions as can be related to coal, lignite, natural gas and oil. The emission rates are coupled to the world fuel production rates by a one year first-order delay, thus taking into consideration the average delay between mining and consumption.

Most of the emissions are caused by the combustion of bituminous coal. Thereby it was not taken into consideration that coal is used as a raw material in the chemical industry. For the FRG, the greatest user of coal chemistry, less than 0.5% of the coal consumption, with an ever decreasing tendency, is used as raw material, thus giving reason to neglecting this portion on a worldwide scale. In 1970 approximately 5.5 x 10^9t CO_2 were produced by the combustion of coal. Additional 1.9 x 10^9 t CO_2 were emitted by the consumption of lignite and about 2.2 x 10^9 t CO_2 by burning natural gas. In the case of oil it was assumed that 8% were used for non-energetic purposes. The figures given in Table 1 are related to the rest of 92% which are referred to in statistic accounts as refined oil fuels. In 1970 about 6.9 x 10^9 t CO_2 were emitted by burning them. Figure 3 gives the total CO_2-emission and the calculated CO_2-emissions since 1860. For 1970 the production was 16 x 10^9 t CO_2 which is about 5% of the net-assimilation rate of the biosphere. In the range of the last 110 years the total man-made CO_2-emission was 450 x 10^9 t CO_2 thus being about 20% of the standing stock of the biosphere. The curve shows that about 70 years were needed to produce the first 150 x 10^9 t CO_2, one third of the total emission. This amount is doubled in another 26 years, and it took only a span of 13 years to produce the last third. From the analogous shape of the curves the approximate exponential growth of the emissions can be deduced.

The given figures are about 6% higher than calculations done in (7). The discrepancy is partly caused by the assumptions made for lignite. The data used here were given in (5) and are more in accordance with the calculations shown in Table 1.

These calculations deal only with the carbon dioxide emitted by the combustion of fossile fuels. Additional CO_2-emissions caused by the production of lime have not to be considered. They amount to about 1% of the total emissions, but are absorbed again when the lime is used.

V. The Analysis of the Carbon Cycle

5.1 The Loop-Structure of the Carbon Cycle

The structure of the carbon cycle is given in Figure 4 by means of a loop-diagram. Thereby the interconnected elements of the system are marked by arrows. The direction of the arrows correspond to the reason/result relation. The signs determine whether a positive deviation of the causing elements produces a positive or a negative deviation of the affected element. A loop with an even number of negative signs is called positive. Usually negative loops stabilize a system. But if there are time-delays causing possible oscillations then stability calculations can only be derived by means of frequency analysis etc.

CO_2-emissions to the atmosphere result in a growth of its concentration which increases the specific assimilation rate of plants. The resulting intensified assimilation leads to a growth of the biomass which by itself reinforces an even more intensified assimilation rate. This process is stabilized by the removal of carbon dioxide from the atmosphere, the carbon of which is fixed in the biomass. This cycle is closed by the death of the plant and the decomposition of the dead organic matter.

The carbon system of the oceans is much more complex. The carbon dioxide is in a state of chemical equilibrium to solutions of different organic and non-organic materials. The resulting partial pressure determines, by the concentration gap between atmosphere and surface layer, the absorption of CO_2 by the oceans. From the surface layer the carbon dioxide is removed by the assimilation rate of the phytoplankton - as is done on the land by a positive feedback loop involving the increasing specific assimilation rate. Part of this carbon is transmitted into dead organic matter of the oceans; partly the carbon follows the food chain of the zooplankton, from where it is released back into the surface layer or is transmitted to dead organic matter, too, which is decomposed and releases the carbon dioxide either back into the surface layer or into the deep ocean water where it is locked for a thousand years. Exchange between these two reservoirs is given by the eddy diffusion due to turbulence generation by wind and ocean currents.

Further complexities of the carbon cycle of the earth arise by an additional feedback loop involving the climate. A growth of the CO_2-concentration of the atmosphere increases the average temperature of the surface of the earth, which too means an increase of the temperature of the surface layer of the oceans. A raising temperature decreases the solubility for carbon dioxide, thus increasing the partial pressure and reducing the CO_2-absorption by the oceans (8). A possible effect of the temperature change on the ocean currents has not been taken into account.

5.2. The Nonlinearity of Plant Growth

In these calculations it is assumed that the net assimilation rate of the plants in the range used here from normal concentration up to 5 times the normal concentration is given with sufficient accuracy by the e-function (9-13)

$$Y = Y_{oo} \cdot (1 - e^{-k/a})$$

with Y being the 320 ppmv to 1 normalized specific net assimilation rate, Y_{oo} being the normalized specific saturation value, k being the normalized atmospheric partial pressure and a being a constant which can be calculated by the normal and saturation value. Field experiments as reported in (13) of poplar, beech-tree, fir, spruce and pine give a good correlation with

$$Y_{oo} = 3$$

$$a = 2.466$$

As can be easily shown this means that a 10% increase of the CO_2-concentration causes a nearly 8% increase of the specific net assimiliation rate. This is in good accordance with (8) where an increase of 5 to 8% is assumed. Nevertheless it must be stressed that there exist no data which would allow for an exact extrapolation of the measured assimilation rate to the assimilation of forests. Here it is assumed that the indicated percentiles can be used for all ages of the trees and for the growth of new plants.

5.3 The Nonlinearity of the CO_2-solution in Ocean Water

If CO_2 is given into water one gets the following equilibrium reaction:

$$CO_2 + H_2O \longleftrightarrow H_2CO_3 \longleftrightarrow HCO_3^{-} \longleftrightarrow CO_3^{--}$$

One part of the CO_2, which in the following is referred to as pCO_2, is physically dissolved in the water. The rest performs a chemical reaction to carbonic acid which dissociates twice. The dissociation equilibrium in ocean water depends on the free cations (e.g. Mg^+ or Na^+) on the pH-value and on the temperature. A mathematical-chemical description of this solution process fails because of the uncertainty of the parameters. In (14) Kanwisher calculates that a failure of 0.02 units in the pH-value causes a 10% discrepancy in a pCO_2-value which is theoretically computed. Therefore empirically derived laws were used.

The partial pressure of the CO_2 in ocean water is related to the temperature and the sum of the physical and chemical dissolved CO_2 which, in the following, is referred to as $\sum CO_2$. Figure 5 gives the data of a water sample at a salinity of 31.5% (14). In log-scale one gets a set of straight lines the derivative of which is about $4.5\%/^{\circ}C$. Thus the relation between partial pressure and temperature can be described by an exponential law. Furthermore, the almost equal distances between the straight lines lead to the assumption of an exponential growth of pCO_2 due to $\sum CO_2$. This is displayed in Fig. 6 for a constant temperature of $T=20^oC$.

As can be seen distilled water only dissolves 1% of the amount which is taken by ocean water at the same conditions. But this does not mean that ocean water, at the equilibrium state of 320 ppmv, dissolves 100 times more when the pressure is increased. For solving this problem the dashed line gives the tangent of the experimentally-derived curve for ocean water at 320 ppmv. The derivative is a measure of the solubility. At this point (20^oC, 320 ppmv) ocean water can dissolve about 16 times as much as distilled water. Beyond a $\sum CO_2$ of 50 ml/l ocean water then can be treated like distilled water.

VI. The Model Verification

6.1 The Simulation of the Development of CO_2-concentration and Temperature in the Past

As part of the verification it must be recognized that the initial values lead to a stable equilibrium of the model. If this equilibrium is disturbed by the above described CO_2-emissions, the vegetation of the land increases the assimilation rate, which prevents a drastic increase of atmospheric CO_2-concentration. Without any reaction of man in the time between 1860 and 1970 an increase of the biomass of the land by 70% is calculated according to an atmospheric concentration which would not be more than 10 ppmv higher than the basic value.

As was pointed out above, this is less than was reported. Though there are no data on the manipulation of the biomass by man, it can be assumed that no significant increase was realized. On one hand man has reduced the area of forests which account for about 65% of the biomass of the land. But on the other hand new areas were cultivated and by artificial treatment the specific density of carbon content per unit of area was increased. By introducing a rate of man-made reduction which is set proportional to the growth of the biomass, the increase can be easily modified. These emissions are not identical with the emissions by forest fires, which are about 0.1 x 10^9t carbon per year (15). Therefore the time constant of a first order delay for the reduction of the biosphere would be more than 5000 years.

If it is assumed that man reduced the increase of the biospere by a time constant of 6 years one gets the simulation run which is given in Figure 7 and fits in well with concentration data report from Mauna Loa. The difference in the last 15 years is less than 0.5 ppmv. But this is the only justification of the time constant which thus takes account of the manipulation by man and the nonlinear extrapolation of plant growth to growth of large areas of different kinds of forests. Therefore the sensitivity of these assumptions will be tested. This leads to the assumption of a basic value for the 19th century of 295 ppmv. In 1970 the growth of the biospere was 3% and the concentration gap between atmosphere and surface layer of the oceans was 1.7 ppmv, thus causing a net exchange rate into the oceans of about 0.65 x 10^9t carbon whereas the emissions of 4.5 x 10^9t of carbon being about 7 times as high.

In (16) Budyko gives the development of the temperature of the earth and the data of changes in direct solar radiation. A correlation of temperature changes and changes in solar radiation each given in an average of 10 year intervals can be proven. However, it is thought that an additional effect was superimposed which was caused by carbon dioxide. Therefore the following mathematical formulation was tested.

$$\tau \cdot \dot{\Delta T} + \Delta T = V_{rf} \cdot (C'_s \cdot \Delta S + C_{co_2} \cdot \Delta CO_2)$$

$$C'_s = \alpha \cdot \beta \cdot C_s$$

with

ΔT = change in temperature (^oC)

V_{rf} = amplifying factor for the assumption of constant relative humidity

ΔS = change in direct solar radiation (%)

ΔCO_2 = change in atmospheric CO_2-concentration (ppmv)

C_s = temperature constant of solar radiation (^oC/%)

C'_s = temperature constant of direct solar radiation (^oC/%)

C_{co_2} = temperature constant of CO_2 (^oC/ppmv)

τ = time constant for equilibrium between atmosphere and surface layer of the oceans (a)

α = parameter with regard to the Mie effect

β = percentage of direct solar radiation

Thus no influence of the dust-load of the atmosphere on the radiation budget of the diffuse radiation is taken into consideration. The parameters $C_s = 0.73^oC/\%$, $V_{rf} = 1.75$, $C_{co_2} = 2.36^oC/300$ ppmv, $\alpha = 15\%$, $\beta = 48\%$, $\tau = 7a$ lead to the simulation run given in Figure 7 which approximates the temperature curve of the northern hemisphere which was corrected by the influence of the data taken near to densely populated areas having a high waste heat production. (17) A better fit of the simulation runs to the real curves can be achieved by a speculative decrease of the solar radiation influence and an increase of the carbon dioxide effect, thus giving reason to the possibility that the CO_2-effect was underestimated by Manabe.

6.2 The Simulation of the Suess-Effect

By the combustion of fossil fuels carbon dioxide, which is free of the C-14 isotope, is emitted into the atmosphere thereby diluting the natural ratio of the isotopes. In order to calculate this so-called "Suess-Effect" the CO_2-model was built as a tandem-model. By computing the input output and decay rates it is possible to stimulate the C-14/C-12-ratios as relative concentrations in each level of the model. A correct reproduction of the Suess-effect data of the past is part of the verification of the model. With regard to the input data used in 6.1 a Suess-effect of 2% is calculated for the time period between 1860 and 1950 which was estimated to be a reasonable value (8) and has grown to be about 4% in 1970.

The theoretical equilibrium equations result in the C-14/C-12 concentration ratios given in Figure 8 being normalized to the concentration of the atmosphere. In order to check the principal behaviour of the model an input function was used which doubled the concentration of the atmosphere. The reaction of the system is described by the curves for the concentrations of the atmosphere and the surface layer of the oceans. The impact on the deep sea water is far beneath the scale used. The concentration ratio in the atmosphere declines by a first order time delay with a time dependent increasing time constant which is about 3 years at the beginning and increases by one year per year. The maximum concentration of the surface layer is reached after 4 years. This and the development in the other system elements causes a steep increase in the time constant of absorption from the atmosphere and approximates the time constant of the deep sea water exchange of more than 1000 years. Although these calculations cannot be applied directly to the real measurements taken after the atmospheric bomb tests, because the equilibrium was already disturbed at that time, the results have a good analogy to these data and the thereby derived time constants (18, 19).

VII. The Analysis of the Future

7.1 The Calculations of Future Use Rates of Primary Energy Carriers

The input data for the above described model of the carbon cycle of the earth, the use rates of fossile fuel consumption, are derived from a model developed by Voss (20) which tries to simulate the interactions of the system man-energy-environment on a global scale. The basic structure of the model is given in Figure 9 which shows the feedback loops considered. The following relationships are treated in the six sub-systems:

1. The population sector describes the dynamic of population growth by calculating the birth and death rates with regard to the average income and the environmental situation.

2. The industrial sector describes the interactions between investments, labour and industrial production.

3. The capital sector describes the process of capital stock growth by investment and depreciation rates.

4. The environmental sector calculates emissions, absorptions, environmental protection and the

costs of environmental strategies.

5. The raw material sector computes mineral resources, mining and recycling rates.

6. The energy sector describes the inter-fuel substitution process of primary energy carriers with regard to use rates, availability indices, prices and handling characteristics.

The assumption which led to the data sets used in the following as input variables to the CO_2-model can only be briefly described. More detailed explanations are given in (20).

7.2 The Model Behaviour with Regard to an Optimistic Equilibrium Strategy (Base Case)

7.2.1 The Result of the Base Case Assumption

As estimated by different studies (21-24), one result of the calculations done by Voss is that the total system of man embedded in his environment has to be carefully planned in order to avoid a breakdown of the whole system when the limits to growth come into the picture. But equilibrium situations are not at all unimaginable. The following example of a future, which is not thought to be unrealistic with regard to very optimistic assumptions, is based on the strategy:

- Stabilization of world population
- Environmental protection at high costs
- Conservation of mineral resources by high grade recycling
- Conservation of fossil fuels to enlarge the basis for raw materials.

Optimistic assumptions on the development of nuclear power, as forced implementation of the advanced generation of reactors after 1985 considering the high substitution potential of HTGR's (high temperature gas cooled reactors) by coal gasification and later feasible water splitting, lead to energy use rates as given in Figure 10.

The situation of the world can be characterized by a stabilization of the population in 2050 at about 8 billion people having on average the material standard of living equivalent to the present U.S.A. The primary energy consumption is stabilized at about 80 x 10^9t CE (coal equivalent) per year, the percentage of nuclear power being more than 90% in the year 2100. These data imply that at the time of the largest increase of nuclear power about 100 nuclear power plants each having a size of 5GWe have to be installed. In spite of these high percentages of nuclear power one gets the CO_2-emissions given in Figure 11. The maximum of 11 x 10^9t carbon which is more than twice the emissions of today, occurs in about the year 2000. The steep decrease of the emission rate is caused by the rapid increase of nuclear power and the decreasing growth rate of the overall consumption. In 2015 and 2025 all natural gas and oil respectively with their low specific emission factors have been consumed. The increase of coal production having a maximum of 11 x 10^9t CE between 2025 and 2030 slows down the decrease rate of the emissions. It must be stated that for the time span between 1970 and 2100 no distinction between coal and lignite could be made as the Voss-model generates data for the sum of both in tons coal equivalent. These calculations are based on the lower specific emission data of bituminous coal.

Due to these emission rates the CO_2-concentration of the atmosphere increases nearly exponential until the year 2000 up to about 383 ppmv. Then the growth is flattened and approximates a maximum value which is not much higher than the value of 570 ppmv given for the end of the simulation run in 2100. These calculations of the 'standard run (base case)' are based on the important optimistic assumption that man allows a 10% increase of the biomass of land. This percentage was chosen as an optimistic subjective guess. The sensitivity of this assumption will be tested in 7.2.3.1. In spite of the fact that in 2100 the CO_2-emission rate equals todays emissions, no further increase in atmospheric CO_2 occurs because of the altered concentration gap in the oceans.

With regard to a constant atmospheric dust load of a level of 1960 the temperature increase given in Figure 11 is 1°C between 2030 and 2040 and 1.8°C in 2100 according to the temperature of 1970.

7.2.2 The Time Related Distribution of the CO_2-Emissions for the Base Case Calculations

As the above described simulation run is taken as the base case and as the following strategies are described with regard to these calculations a more detailed description of the distribution of the CO_2-emissions to the different levels is needed. The rough structure is given in Figure 12. Until about 2000 the assimilation rate of the plants on land is increased by 35% caused by the increase of specific assimilation rate and the increase of the biomass. This leads to a storage of 60 x 10^9t carbon in living organic matter, thus absorbing in total 31% of the CO_2-emissions. About 50% of the emissions remain in the atmosphere causing an increase in the concentration of about 30%, corresponding to 383 ppmv which is very close to a prognoses of 279 given in (8). The rest of 19% is absorbed by the oceans. A surface layer having a size of 100 m dissolves only 4% thereby increasing its carbon content by 2%. But if only the physically dissolved CO_2 is considered which is as described above only about 1% of the overall content, then the increase is about 200%. 11% are stored in the deep sea and the dead organic matter of the oceans. About 4% are calculated to be sediments. A minimal amount is stored in the biomass of the oceans. Nevertheless, it has to be regarded as an important factor in the absorption process because of its high rate of carbon throughput. The gross assimilation rate of the phytoplankton (35 x 10^9t C/a) is of nearly the same size as the gross transport of carbon from the surface layer of the oceans to the deep ocean water.

In 2100 the accumulated emissions are more than 1100 x 10^9t carbon. 52% remain in the atmosphere. This percentage is even higher than in 2000 because of the nonlinearity of partial pressure in sea water. Because only a 10% increase in the mass of plants was allowed, CO_2 on land after 2000 can only be stored in dead organic matter due to the increase of the assimilation rate.

The simulation of the Suess-effect calculates a dilution of 12% in 2000 and 24% in 2100. These numbers are derived without calculating the C-14-emissions of nuclear power plants.

7.2.3 Some Sensitivity Calculations

7.2.3.1 The Influence of the Biosphere on Land

The data used for the standard run are upper estimates of the mass of organic carbon on land and of the flow rates. To calculate the influence of these assumptions the data were changed to estimates given in (25). This means a reduction of

- the net assimilation rate by 50%
- the living organic matter by 25%
- the dead organic matter by 22.5%

In comparison to the base case calculations this simulation run results in only a 7 ppmv increase of concentration in 2100. This is less than 3% of the computed increase. This remarkable stability with regard to the land parameters is due to the fact that the concentration is somewhat higher during the whole period thereby causing a higher absorption rate of the oceans. This justifies in retrospect that with regard to diverging estimates no disaggregation of the organic carbon on land was undertaken.

The influence of the percentage of plant increase is much larger. Data on the change of the forests in the world are not available. Calculating a constant level after 1970 results in an additional increase of atmospheric concentration by 27 ppmv or of temperature by 0.18°C. Pessimistic estimates calculate a reasonable reduction of the forests in the world by increase of desert areas and by clearing of virgin forests resulting in a change to steppes or agricultural areas. According to (8) the specific carbon density of forests is 21 x 10^3t/km^2 in comparison to 11 x 10^3t/km^2 and 8 x 10^3t/km^2 for agricultural areas and steppes, respectively. A pessimistic estimate is given by a 50% change of forests into agricultural land and steppes each taking 50%. This would result in a 15% reduction of the biomass on land. If a linear decrease by 15% in the time period between 1970 and 2050 is assumed and emitted as CO_2 one gets the curves given in Figure 13. An additional increase by 95 ppmv is calculated corresponding to a temperature increase of 0.6°C. This large effect is understandable with regard to the fact that these emissions would be about 14% of the emission due to the combustion of fossile fuels during this period.

7.2.3.2. The Influence of the Ocean Surface Layer

Though the surface layer of the oceans, as previously discussed, is not able to store a reasonable amount of CO_2 by itself it is one of the most important elements of the system because it links the atmosphere and the deep ocean water. A change of the CO_2-solubility of water can be simulated in the model by decreasing the water temperature e.g. by 5°C. This change causes two effects: firstly the curves given in Figure 5 and 6 are flattened and decrease the feed-back effect of growing partial pressure. Secondly the lower temperature results in a 2% higher carbon level in surface water, the partial pressure being constant. Because of the equilibrium conditions the net exchange rate between surface layer and deep sea has to be constant, therefore, the average delay time of carbon in surface layer has to be decreased by 10%. In spite of this change in the parameters the difference in 2100 is only 1 ppmv corresponding to 2%.

Estimates of the size of the surface layer of the oceans range between 100 m and 75 m. In order to test the sensitivity of the model with regard to this parameter the value of 100 m which was chosen for the standard run was changed to 75 m, which results in a smaller gap of partial pressure between atmosphere and ocean. As the net exchange rate is proportional to this difference the atmospheric concentration is increased up to 2.5 ppmv. A further increase is counteracted by an increase of the gap between surface and deep ocean water.

As the estimates of the temperature effect of atmospheric CO_2 are very fuzzy its feedback on the partial pressure was not taken into consideration. The difference was simulated to be 6 ppmv in 2100. Thereby this assumption is the most sensitive of the assumptions tested in this chapter, and sophisticated descriptions of the diffusion of carbon in water will not influence the results significantly (26).

Additional sensitivity studies were performed for the time delay of surface water, the biological half life of carbon, the distribution parameters for dead organic matter and use rates of the phytoplankton and the exchange rates between atmosphere and surface layer. Even a 50% reduction of the exchange surface of the oceans, e.g. by the approximate 2 x 10^6t oil which are discharged into the sea each year (8), does not result in a significant change in the simulation runs. This stability is due to the large number of interacting feedback loops and to the fact that usually no single parameter can be changed but whole parameter sets have to be used with regard to the equilibrium conditions. The only sensitive parameter is given by the assumption on the increase or decrease of the biosphere of the land.

7.3 The Model Behaviour Considering no Nuclear Energy

The base case (or standard run) described above gives the model behaviour under very optimistic conditions for the implementation of nuclear power. In the following the implications of an energy supply strategy will be discussed which has, for some reasons, to rely only on fossile fuels.

With regard to these conditions the Voss-model computes consumption rates of fossil fuels as given in Figure 14. The exponential growth of the overall consumption slows down soon after 1980 and reaches a maximum of 55 x 10^9t CE/a in the middle of the next century. During the next two decades the main percentage of energy consumption would be provided by oil and natural gas, because of their superior attributes with regard to handling and environmental aspects. The percentage of natural gas consumption would grow higher than oil and coal. Because of that reason its resources are depleted in 2020 whereas oil would be available on a significant scale for another 15 years. After this time period the whole energy needs would have to be met by coal if non-fossil and non-nuclear energy resources such as solar, geothermal, wind, waves etc. are not taken into account. At the end of the next century there will be a breakdown of the system due to the depletion of energy and material resources if lower estimates are considered. Optimistic estimates have just the effect that the maximum consumption rate can be provided for another 30 years. Of course, it is far beyond the possibility of the model structure to simulate the crisis. But the breakdown of the model system strongly indicates that there will be a crisis.

These consumption rates of fossile fuels result in CO_2-emissions as given in Figure 15, the maximum of which is about 40 x 10^9t carbon/a. The resulting atmospheric CO_2-concentration would increase up to 1500 ppmv corresponding to five times the natural concentration and would lead to a temperature increase which is already more than 3^oC in 50 years from now. The maximum value of 9^oC temperature increase must not be taken too seriously because there certainly will be a saturation effect in the temperature - concentration relation which has not yet been estimated. But the number calculated here with regard to a linear relationship (as usually done in literature) gives the correct size of the effect which means that the development of the system man - energy - environment would already reach a limit due to the CO_2-emissions long before the depletion of the resources would restrict the system. It does not matter for this result if lower or upper estimates of the resources are used. An energy supply depending exclusively on fossil energy would result in unpermissably high temperature changes within a period of 50 years.

7.4 The Model Behaviour Considering Nuclear Power Plants of the First Generation

As the CO_2-emissions calculated in 7.3 are much too high, the behaviour of the system was analysed taking into consideration the first generation nuclear power plants. The implementation of mostly LWR (light water reactors) having a conversion factor less than 50% leads to a very insufficient use of the natural uranium resources. The result of such a strategy is given in Figure 16. The curve of the overall primary energy consumption rate is nearly identical to that given in Figure 14. Here just some coal is substituted by nuclear energy. At the end of this century nuclear power accounts for about 25% which increases rapidly to 50% after the depletion of oil and natural gas resources. But the growing demand cannot be provided by nuclear power because of increasing costs of fuel supply by low grade uranium mining. Therefore the increasing demand is met by coal and after 2050 there is even an absolute decrease of nuclear power.

With regard to these consumption rates of fossil fuels CO_2-emissions are calculated as are given in Figure 17. The implementation of nuclear power results in a slower increase as displayed by Figure 15 and even a decrease for a period of 20 years after 2000. The reason why this decrease is not so obvious as the decrease of fossile fuel consumption is given by the worse emission rates of increasing coal consumption. Nevertheless the atmospheric concentration is doubled between 2030 and 2040 and increased to 1300 ppmv in 2100 still having a positive steep gradient. The temperature is increased by 3^oC in the middle of the next century and by about 7.2^oC in 2100. It can be deduced by these calculations that the implementation of first generation nuclear power plants is not able to solve the CO_2-problem but gives just a little bit more time.

7.5 The Model Behaviour with Regard to CO_2-Emission Control

7.5.1 The Limit to a Temperature Increase

For the above-mentioned three strategies of fossil fuel consumption the resulting concentrations and possible temperature increases were calculated. Consequently it has to be discussed which increase of temperature would be permissable without running the risk of global climatic changes. At this time there is no definite answer. Vague estimates result in the possibility of glacial periods being caused by a 3% change in solar radiation and give a 1% limit for a man-made change (27). With regard to the infrared radiation of the earth surface this would correspond to a 0.77°C increase in the temperature of a black body.

On the other hand the data used in these calculations need verification by more-dimensional models which are under construction in several parts of the world (28). The values calculated by Manabe are disagreed with by several authors (29, 30) but give the best calculations available at this time (8, 31, 6). The calculations described in 6.1 give reasons for the estimate that the temperature effect of carbon dioxide could be even higher than 2.4°C per doubling of concentration (see Figure 7). A reduction of the temperature increase could in principle be achieved by three different strategies: firstly a reduction of fossile fuel consumption, secondly the direct emission of CO_2 into deep ocean water (pipe lines) and thirdly counteracting the temperature effect by altering the radiation balance of the earth (dust load of atmosphere, changing the absorption coefficient of the earth surface). Dealing with the last two points, there exist only very rough estimates (32). Therefore in the following is given a calculation which leads, by reduction of fossile fuel consumption to a temperature increase of about 1°C.

7.5.2 The Model Behaviour with Regard to a Reduction of Fossile Fuel Consumption

These calculations would request a coupling of the Voss-world-model to the CO_2-model which is at the present time not possible because of computational problems, but will be performed after translating the models into a different programming language. The Voss-model calculates the substitution process of the different primary energy carriers by assigning benefit indicators which are derived from costs, availability and handling attributes and determine the relative benefit which, with regard to a time delay, causes the percentage of the overall consumption. In order to represent approximately the influence of the CO_2-problem the benefit indicator of coal was multiplied by a time dependant factor which lowers the benefit of coal to zero in 2100. The result is an additional substitution of 6.5×10^9t CE/a which is about 90% of the world energy consumption of today. The resulting primary energy consumption rates are given in Figure 18. Solar, wind and geothermal energy can be included only when their relative benefit is equal to that of nuclear power. For more sophisticated calculations especially, the environmental sector of the Voss-model has to be disaggregated. The resulting emissions are given in Figure 19 and lead to a maximum temperature increase of 1.1°C in the middle of the next century.

VIII. Summary of CO_2-Analysis

The calculations described above gave the concept of an analysis of the carbon cycle of the earth by means of coupled nonlinear differential equations. Basic results were:

- A remarkable stability of the results with regard to a change of parameters were observed.
- A change in the mass of the biosphere is the critical parameter of the system. A reduction of the world forests would increase the CO_2-problem significantly.
- The estimates of the time constant responsible for the exchange rate between atmosphere and surface layer of the oceans have no significant influence on the results. Therefore a further

increase of atmospheric concentration due to oil spilled into the oceans need not be considered.

- An increase of the atmospheric CO_2-concentration to 1500 ppm (by volume) in 2100 corresponding to a probable temperature increase estimated to be in the range of $9^{o}C$ with regard to an energy supply strategy based solely on fossile fuels was calculated.

- These data would change to 1300 ppmv and $7^{o}C$ with regard to an energy supply strategy based on nuclear power plants of the first generation.

- These data would change to 570 ppmv and $1.8^{o}C$ increase above the present average with regard to optimistic estimates on a forced implementation of advanced reactors. All results are based upon optimistic assumptions of the assimilation rates of the biomass on land and in the oceans.

- A control of the CO_2-effect seems to be possible by an increased substitution of nuclear power and new developed energy resources. More sophisticated models have to analyse the build-up of nuclear system with regard to the capital constraints and industry capacities.

It must be stressed that the development of sophisticated models to calculate the temperature effect of atmospheric CO_2 is urgently needed as the calculations described here

(a) result in large increases of the future CO_2-burden to the atmosphere,

(b) give reason to estimate that the CO_2-effect could be even larger than calculated by Manabe.

The calculations given here are based on the data derived by Manabe and do not include a change in the future dust-burden to the atmosphere. As the man-made dust emissions today are orders of magnitude less than natural emissions(33) it is assumed that oscillations will occur in the range of the data given in the past as were included in the figures.

IX. The Analysis of the C-14 Burden

9.1 The C-14 Problem

The simulation of the flow of Carbon-14 which was used to verify the CO_2-calculations by estimating the Suess-effect (industry effect) can be used to calculate the radiation exposure due to naturally produced and anthropogen C-14. The Carbon which is inbuilt into living organic matter consists out of that isotope ratio which is given by its food sources, the atmosphere and biosphere. Therefore the calculation of the resulting gonard dose depends only on the isotope ratio and not on the absolute concentration of C-14 in the atmosphere. So two counteracting processes are superimposed.

On one hand the absolute mass of C-14 is increased by man-made production and accumulates because its half-life of 5730 ± 30a(31) which is long in comparison to the time periods regarded here, causes decay rates which are very small in comparison to the emissions. On the other hand the C-14-free CO_2-emissions of fossile fuel consumption dilute the relative concentration and lead to a decrease of the radiation exposure. In the following the superimposition of these counteracting effects is analysed.

9.2 The Natural C-14

The construction of the C-14 model is such that the natural relative concentration of the atmosphere is used as input parameter. Then the concentrations of the other levels of the carbon cycle and the natural production rate are calculated by the model with regard to the equilibrium conditions. The natural isotope ratio of the atmosphere is 6.1 p Ci/g Carbon (31, 32) and leads to a natural production rate of 25.6 - 26.5 x 10^3 Ci/a. This is in good accordance with (34, 35) where about 0.03 MCi/a are estimated. Therefore the total amount of C-14 on earth is 212-219 M Ci 1.8% of which is in the atmosphere and 90% is in deep ocean water. The lower values correspond to a mean residence time in the surface layer of the oceans (size 100 m) of 30 years, the upper values of a residence time of 20 years.

The resulting concentrations are given for several levels in Figure 20. With regard to the long half-life of C-14 the time constants of the biosphere are negligible. Reasonable concentration differences occur in the oceans. By taking into consideration the natural C-14 concentration of 6.1 p Ci/g carbon the natural radiation exposure (gonard dose) is calculated to be 0.68 mrem/a.

9.3 The Man-Made C-14-Emissions

Man-made Carbon-14 is emitted by the operation of nuclear power plants and reprocessing facilities and by nuclear explosives. No C-14 is emitted by the consumption of fossil fuels. If the age of fossil fuels is calculated to be about 300 million years then the natural concentration decreased due to the comparatively short half-life to

$$C = C_o \cdot e^{-37300}$$

which can practically be regarded as zero.

The C-14 of nuclear explosions is mainly emitted into the stratosphere from which it is removed into the troposphere by a time constant of less than two years. As input data for the following calculations, figures were used as are given in Table 2. The emissions were treated as if equally distributed in the given time periods. These data are very fuzzy. Accoring to (35) and (37) a lower total production of 8 MCi or even 5 MCi respectively was estimated.

The emissions into the atmosphere by the use of nuclear power were calculated by the figures given in Table 3 (38). Carbon-14 is mainly produced by nuclear reactions of C-13, N-14 and O-17. Places of origins are the ambient air at the outside of the pressure vessel and pollutions of the cooling system, fuel rods and structure material. As can be derived by Table 3 the fuel cycle of the HTGR emits nearly three times as much C-14 as that of LWR. The whole amount of the C-14 production is emitted by the reprocessing of the fuel elements. Here, by burning the graphite, the whole amount of C-14 is emitted whereas an especially high percentage of that produced by FBR is estimated to be disposed with the radioactive waste. In the following it was assumed that the emissions of the reprocessing plants have a time delay of 2 years after production.

9.4 The Model Behaviour for the Base Case

As input data for the consumption rates of nuclear power, numbers were taken as given in Figure 10 and as used for the base case calculations of the CO_2-analysis. It was assumed that beginning with the year 1980 the advanced reactors would linearly increase their percentage of nuclear power production up to 100% in 2030, HTGRs and FBRs each taking equal portions as was assumed for PWRs and BWRs.

As Figure 10 gives the nuclear power production as thermal output measured in tCE/a the calculation of the emissions with regard to Table 3 has to include the efficiencies which were assumed to be 33% and 39% for LWRs and advanced reactors respectively. With regard to these assumptions the emissions as are given in Figure 21 were computed. In the equilibrium stage 0.25 MCi/a ot C-14 are emitted by nuclear power plants which, after 2050, means by FBRs. About 5 times as much is emitted by reprocessing plants. It must be stressed that these high emission figures are based on very optimistic estimates of the implementation rates of nuclear power.

The curve of the Suess-effect which was computed to be +1.9‰ in 1950 decreases very rapidly caused by tests of nuclear weapons, crosscuts the level of natural concentration, and has a local minimum of -103‰ in 1965. Then the anomaly declines very slowly, as firstly the C-14-leakage of the stratosphere decreases, secondly C-14 is absorbed by the different sinks of the carbon cycle (the behaviour of the absorption time constant was analysed in Figure 8) and thirdly the C-14 free CO_2-emissions of fossile fuel consumption dilute the relative concentration. The natural relative isotope concentration is not reached but the C-14/C-12 ratio decreases again after 1995. A Suess-effect of about -350‰ is calculated in 2100. Because of the definition of the Suess-effect, positive figures give a dilution of C-14 concentration. By using the percentage of this effect it is quite easy to calculate the radiation burden to man. As the natural burden was estimated to be 0.68 m rem/a this figure has just to be multiplied by this effect. For the year 2100 therefore the radiation dose (gonard dose) due to man-made C-14 is calculated to be about 2.4 m rem/a (Average natural radiation burden FRG about 120 m rem/a).

Figure 22 gives a description of the superimposed dilution and concentration effects. Until 1980 the curves of relative concentration and absolute amount are nearly parallel. This is changed rapidly by the increase of fossile fuel consumption. But because of the high percentage of nuclear power the C-14 emission over-compensates the diluting effect of CO_2-emissions.

The result, as given in Figure 21 and 22 is sensitive to the assumption of the time constant of surface water exchange. A reduction of this average delay from 30 years to 20 years results in a Suess-effect reduction in 2100 from -350% to -310%, corresponding to a change of about 10% at the end of the computational period. On the other hand, a reduction of the CO_2-emissions would result in an additional radiation burden. If, for example, the energy supply strategy of Figure 18 is considered, and no non-fossil and non-nuclear primary energy carriers are considered, a further increase of the Suess-effect to -450% is computed.

9.5 Conclusions of C-14 Calculations

For calculating the future radiation dose due to artificially produced C-14, two counteracting effects have to be considered: the diluting effect of CO_2-emissions and the concentration effect of C-14 emissions by nuclear power plants and reprocessing facilities. For long term calculations the C-14-emissions predominate the CO_2-emissions. Therefore an additional radiation exposure has to be calculated. The dose depends on the estimated energy supply strategies. Optimistic production rates of nuclear power lead to gonard doses which are calculated to be in the range of 2-3 m rem/a with regard to different choices of parameters. Therefore C-14 is a pollutant on which, in the future, more interest has to be concentrated.

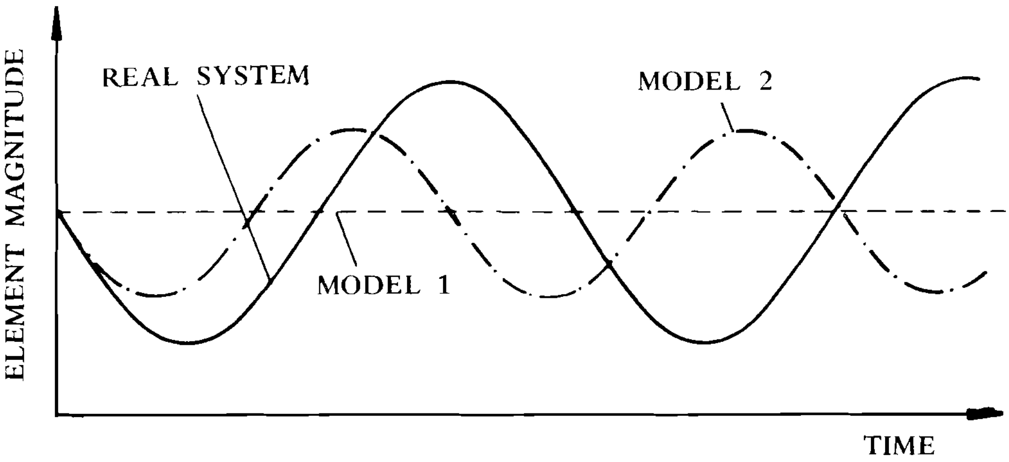

Figure 1. Classifying simulation models (2).

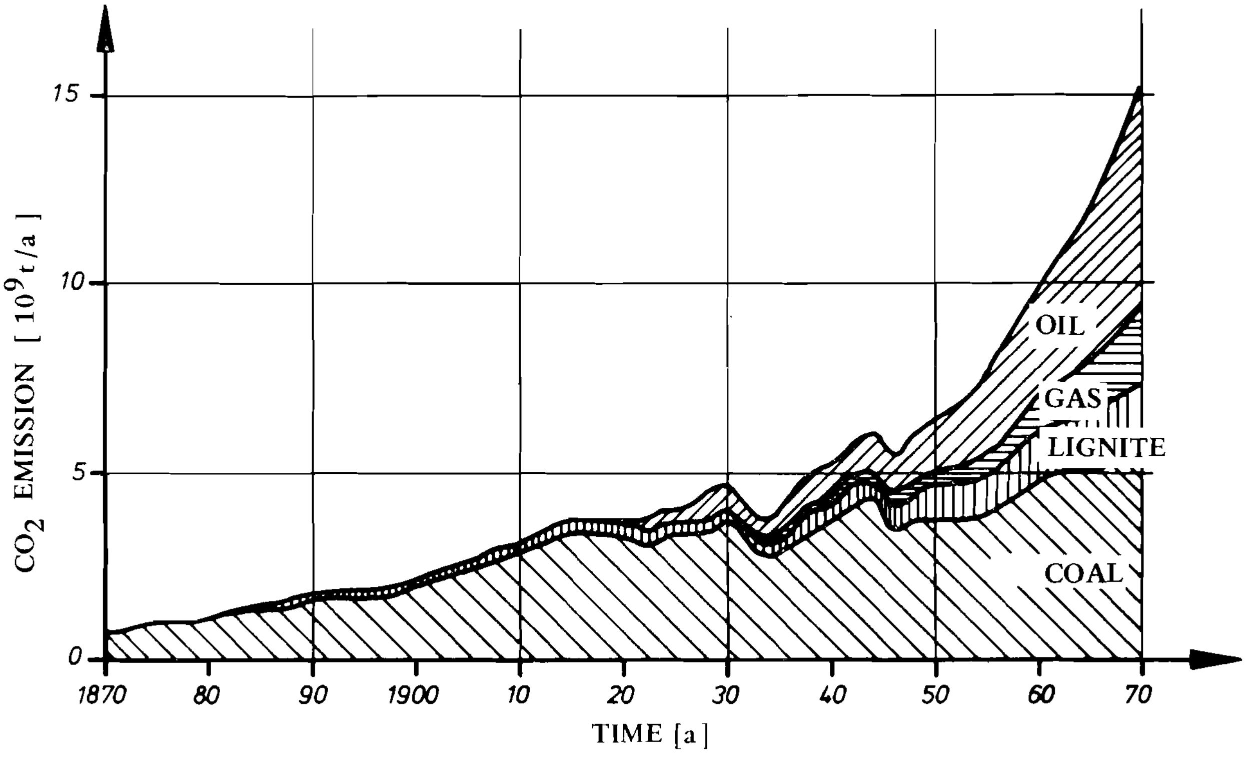

Figure 2. Disaggregation of CO_2 emissions due to the combustion of fossil fuels.

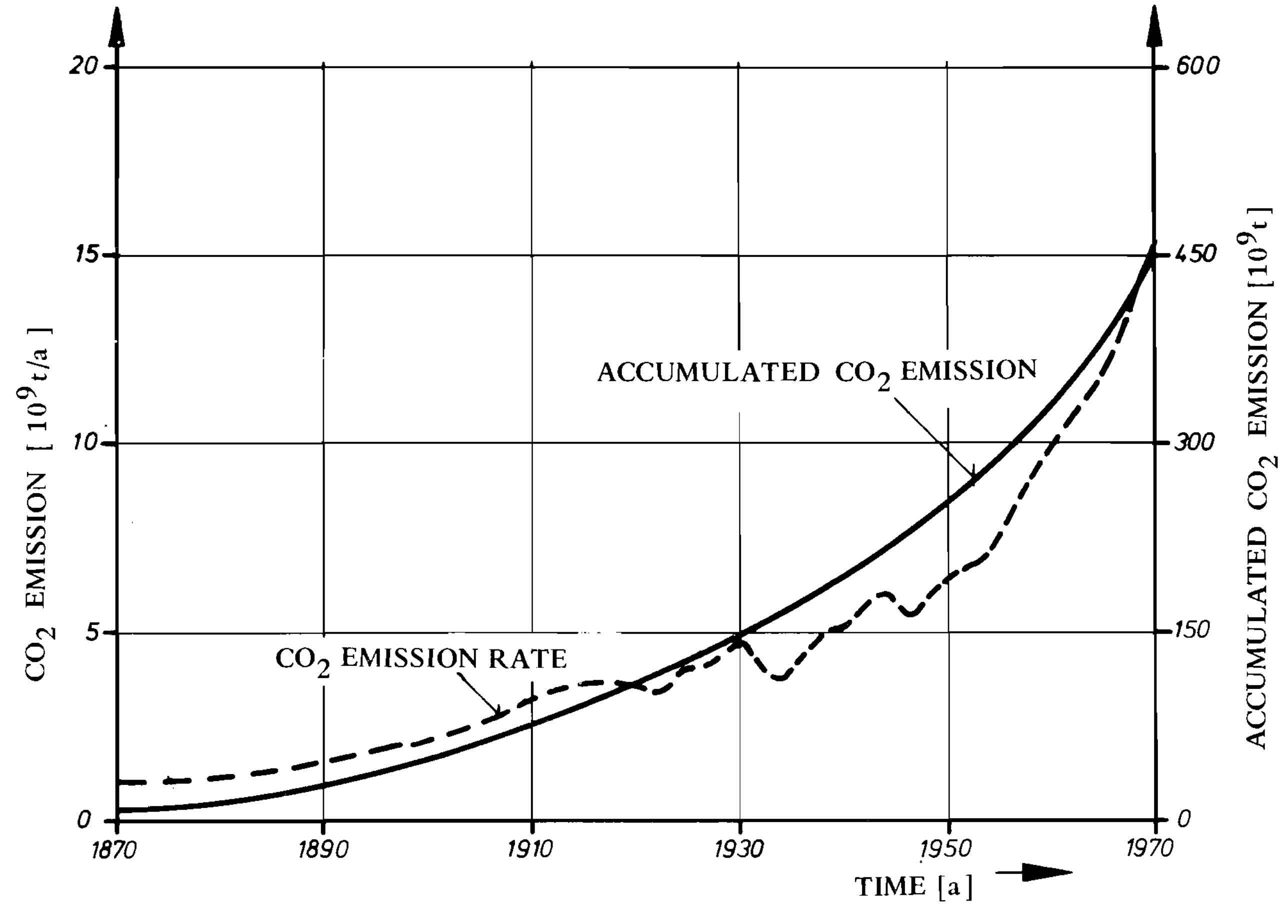

Figure 3. CO_2 emission rates and accumulated CO_2 emissions.

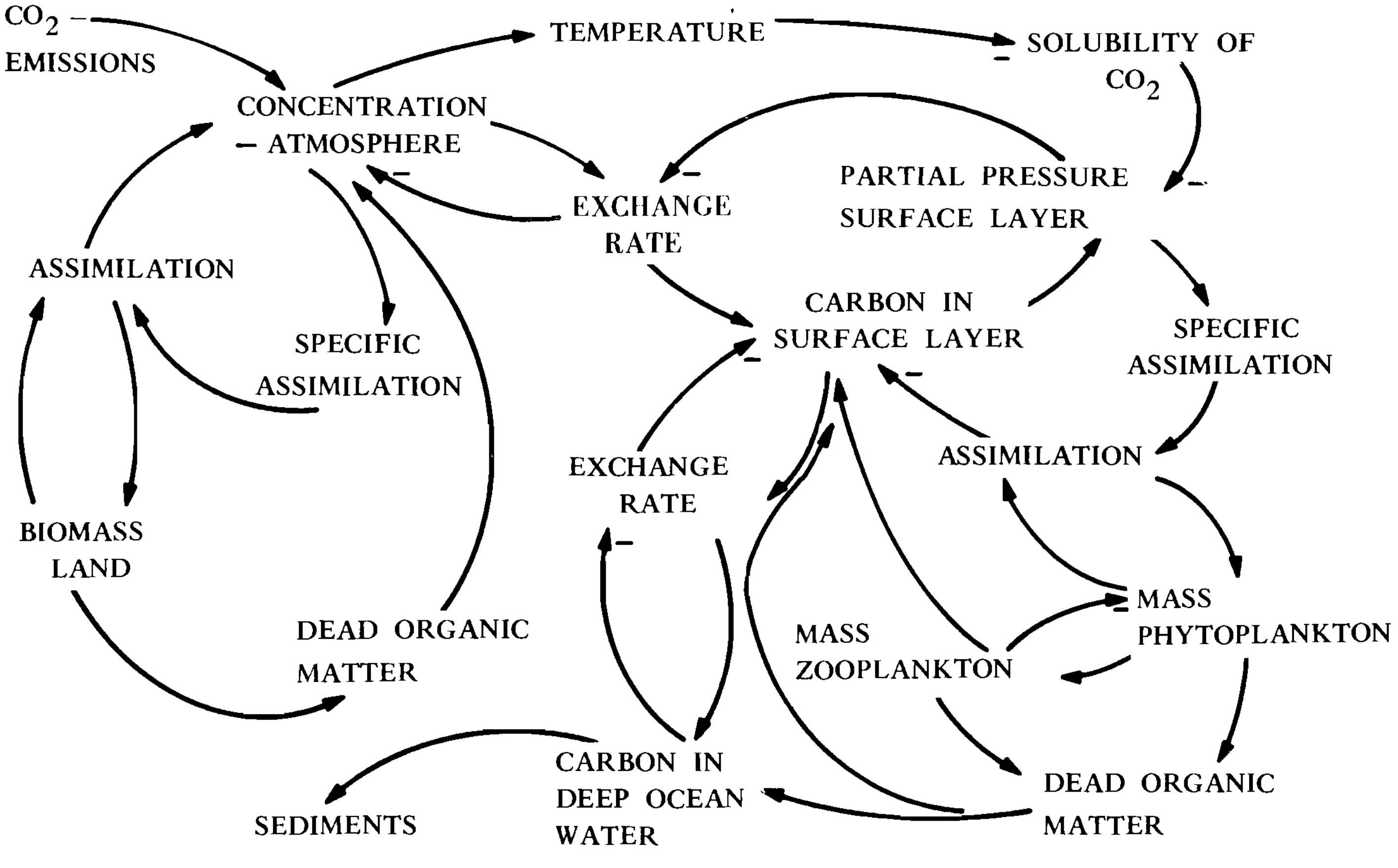

Figure 4. The loop structure of the carbon cycle.

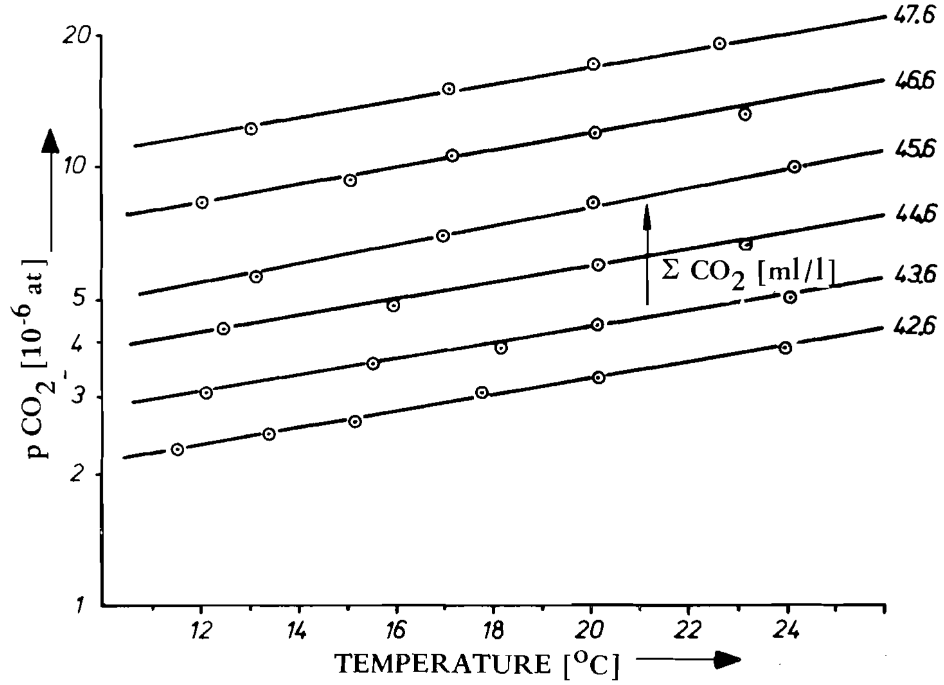

Figure 5. Relation of pCO_2 and temperature at different $\Sigma\ CO_2$ levels. [14].

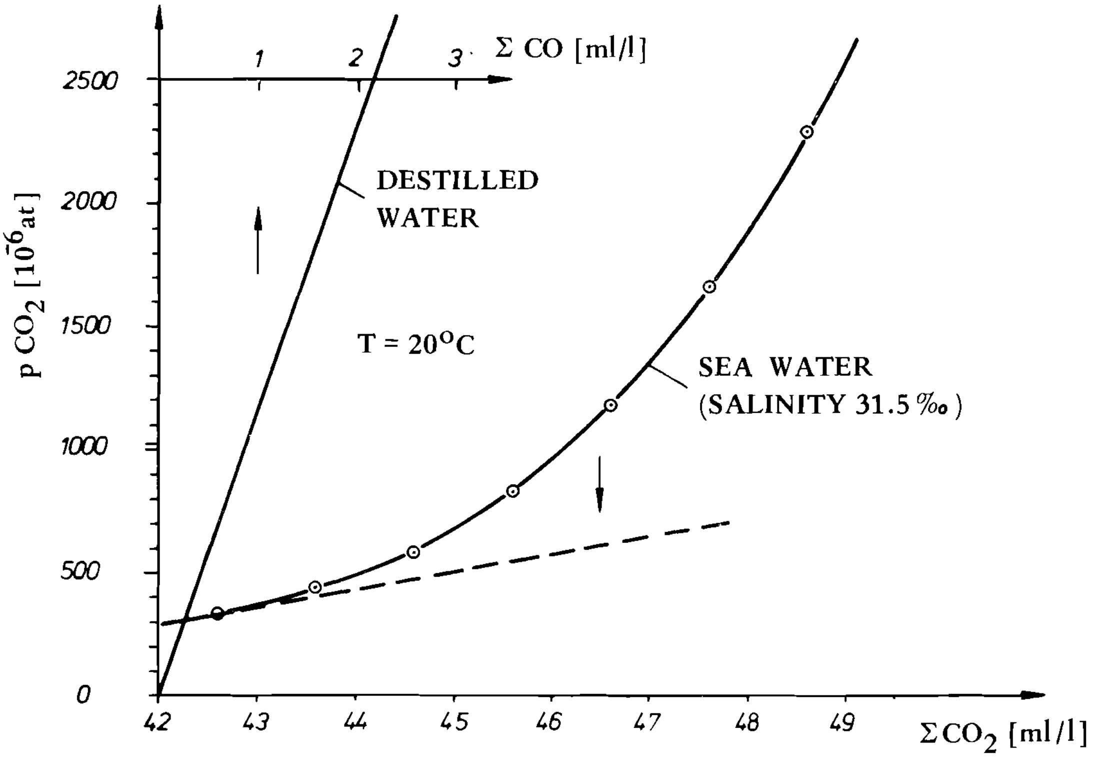

Figure 6. Relation of pCO_2 and $\Sigma\ CO_2$ for sea and destilled water at constant temperature.

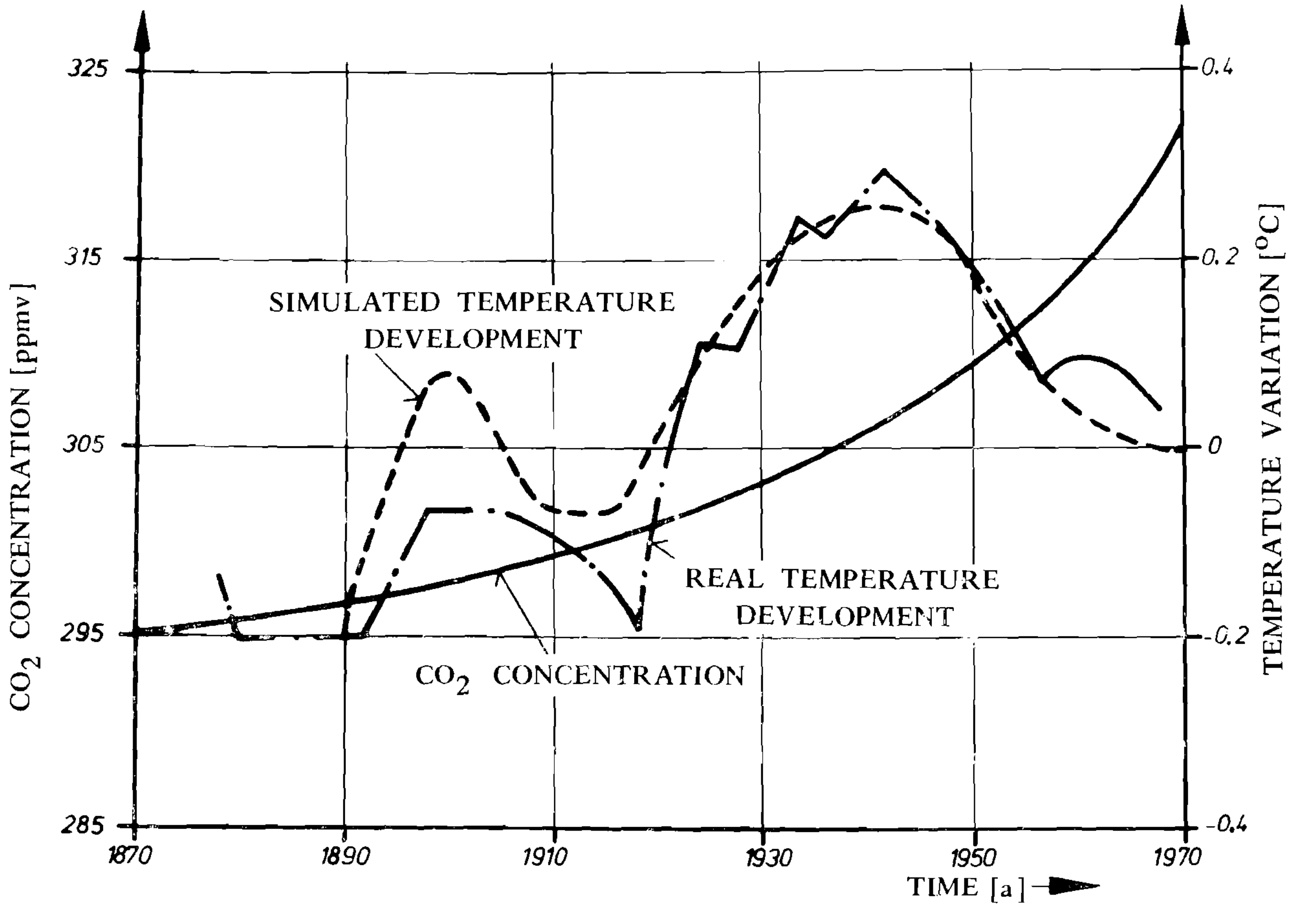

Figure 7. Verification of the standard run.

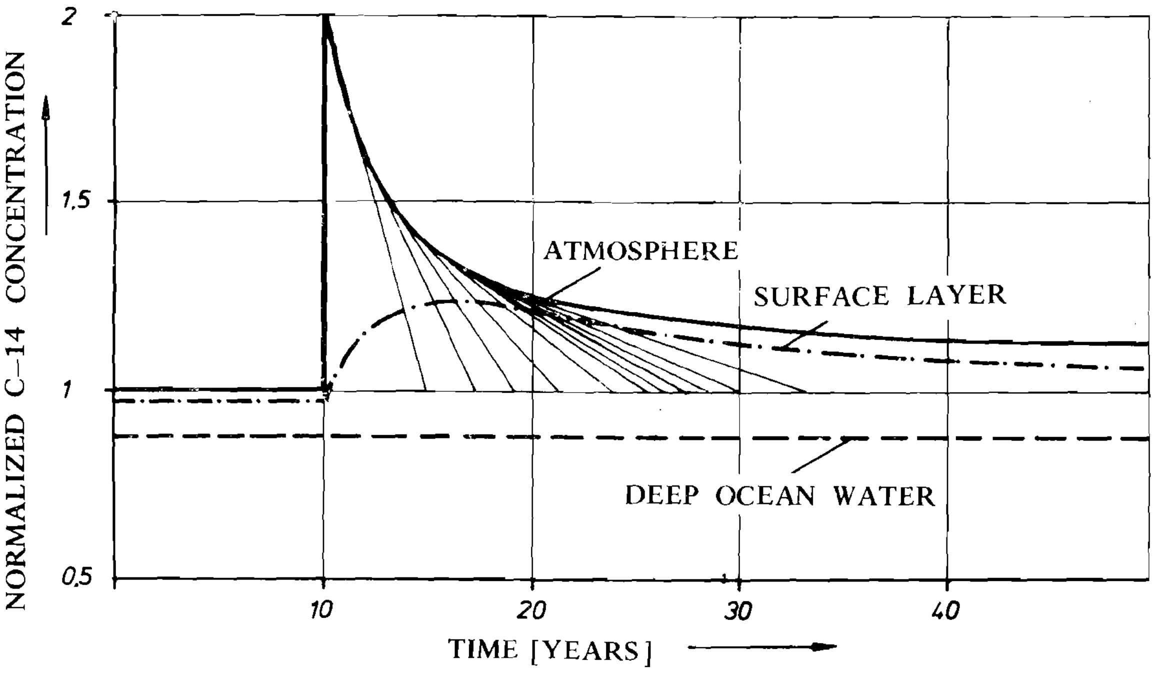

Figure 8. Systems behavior of C-14 model.

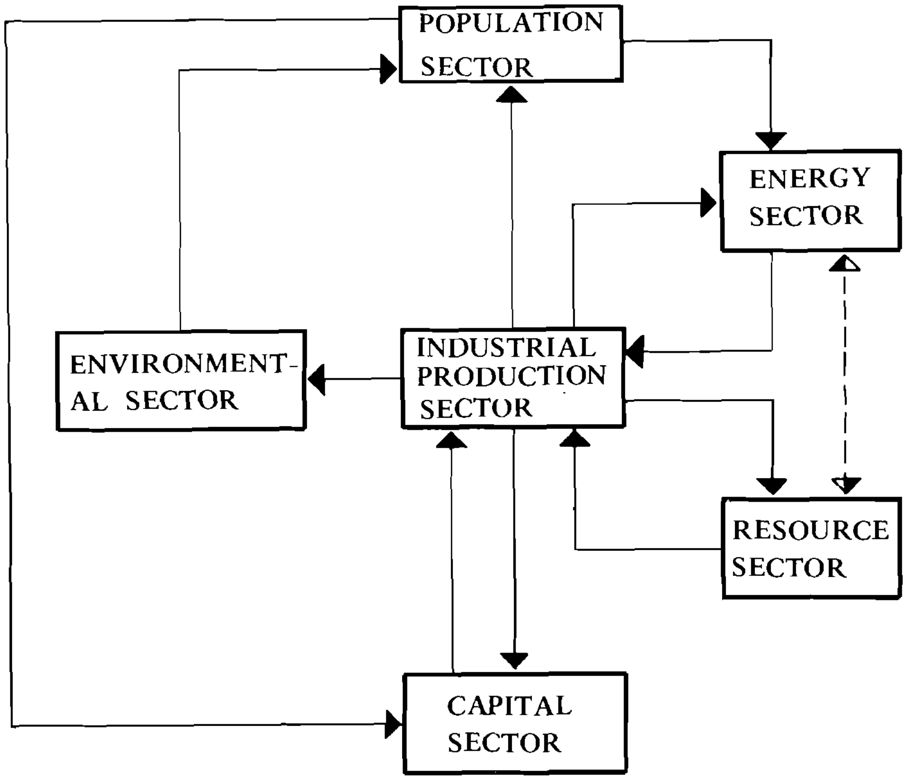

Figure 9. Basic structure of energy model [20].

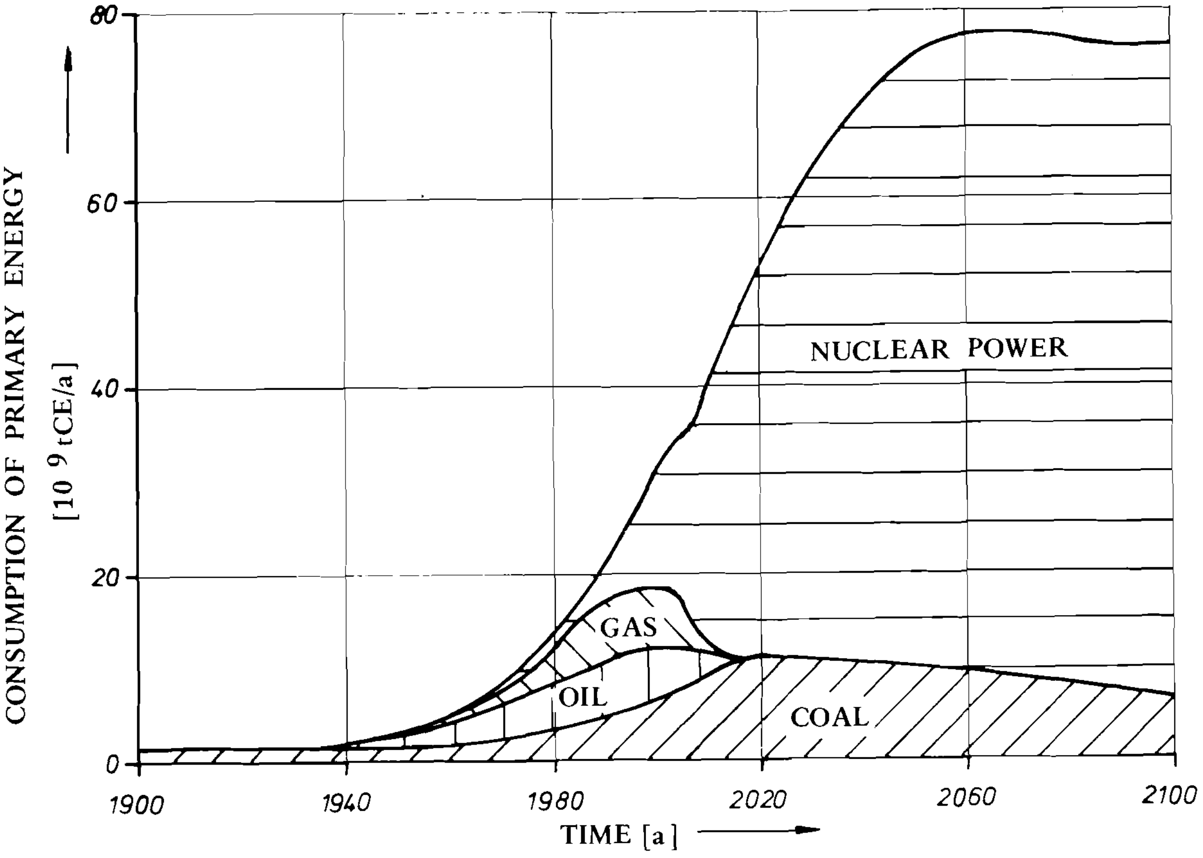

Figure 10. Development of primary energy consumption with regard to an optimistic equilibrium strategy.

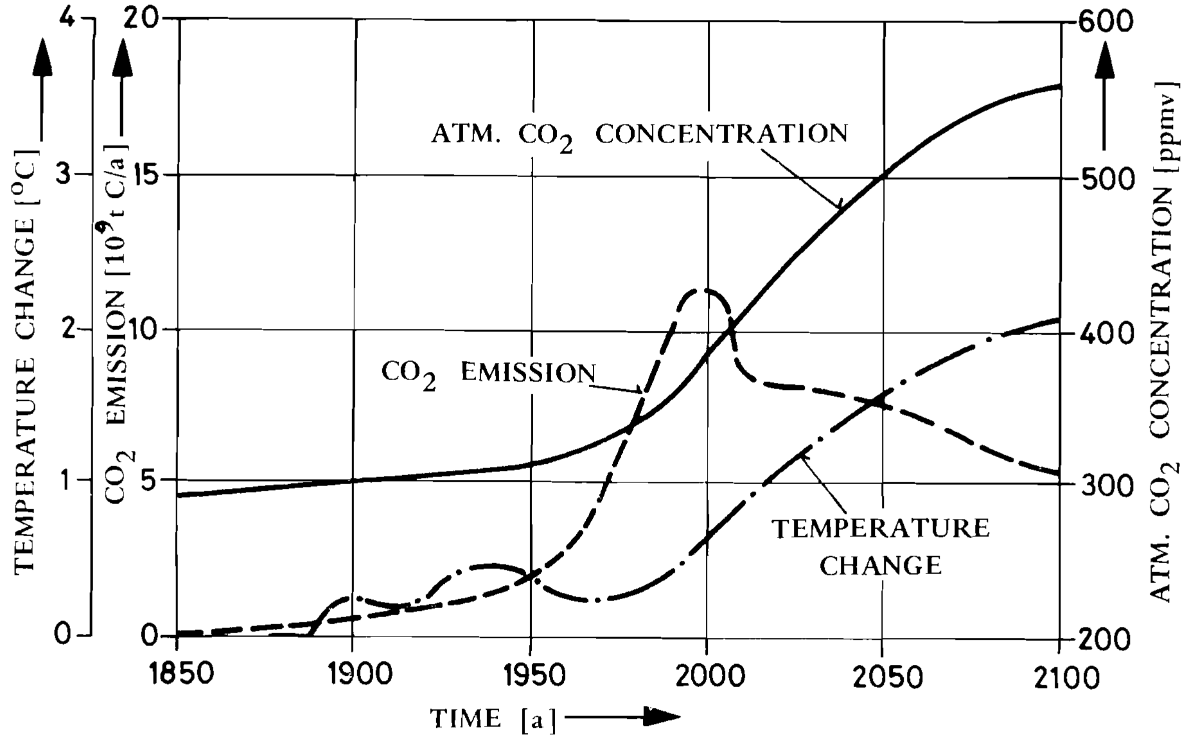

Figure 11. Simulation of the CO$_2$ burden to the atmosphere with regard to an optimistic equilibrium strategy.

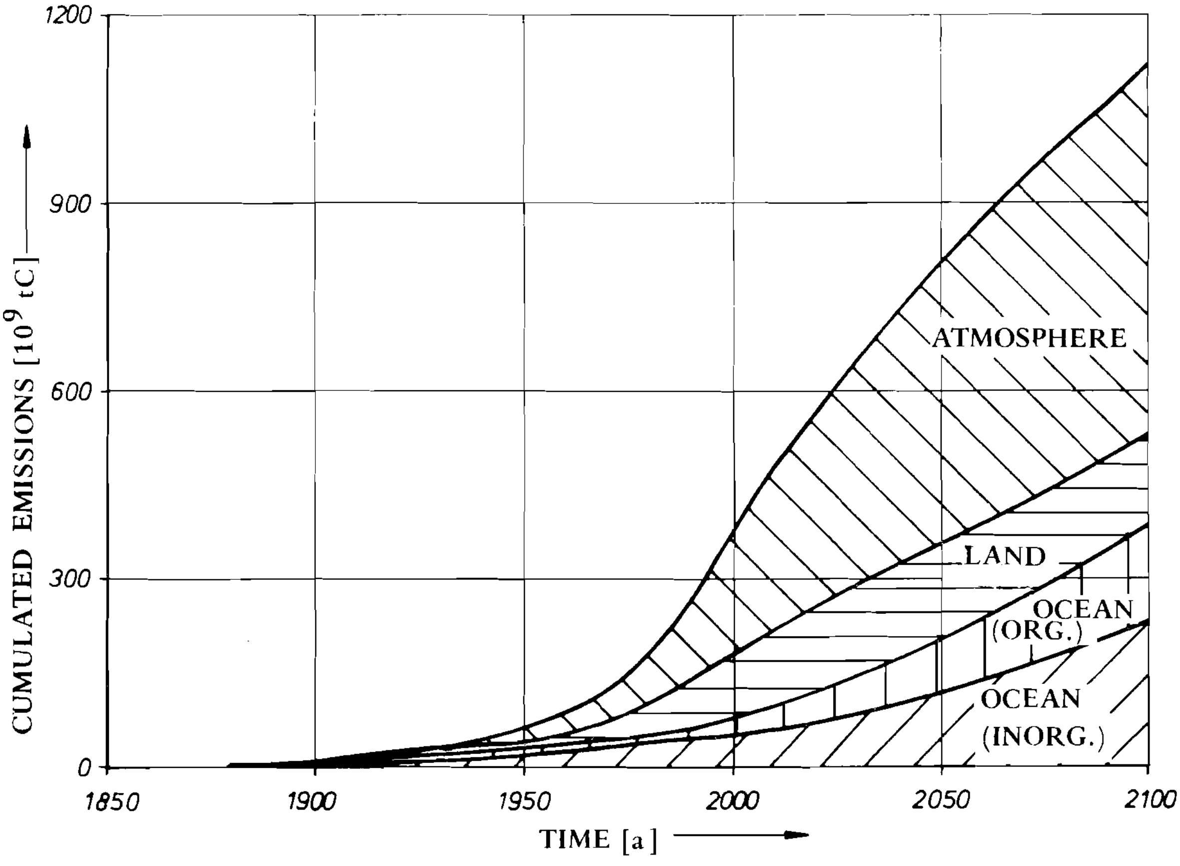

Figure 12. Distribution of CO$_2$ emissions with regard to the base case assumptions.

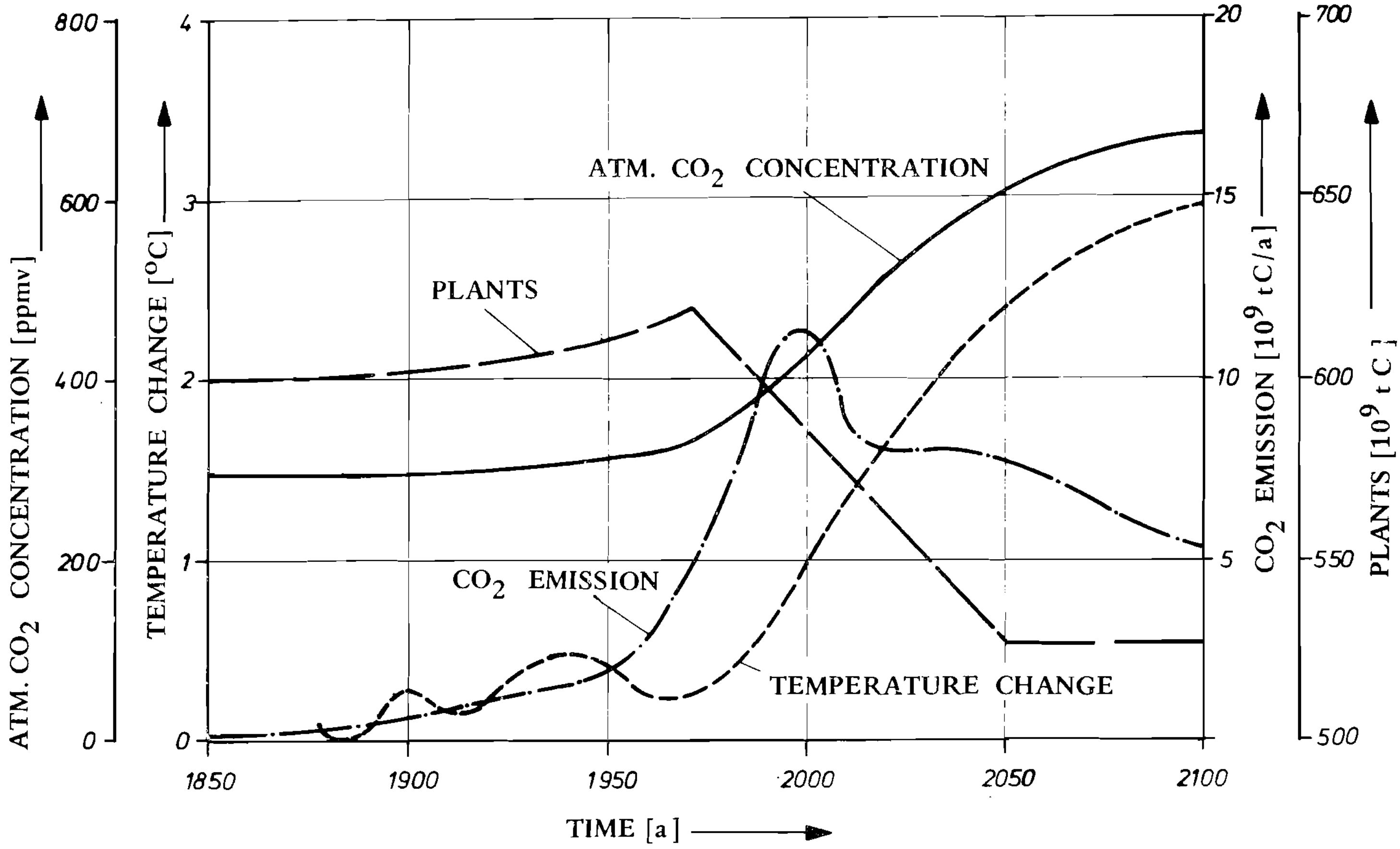

Figure 13. Influence of a pessimistic estimate of the decrease of world forests.

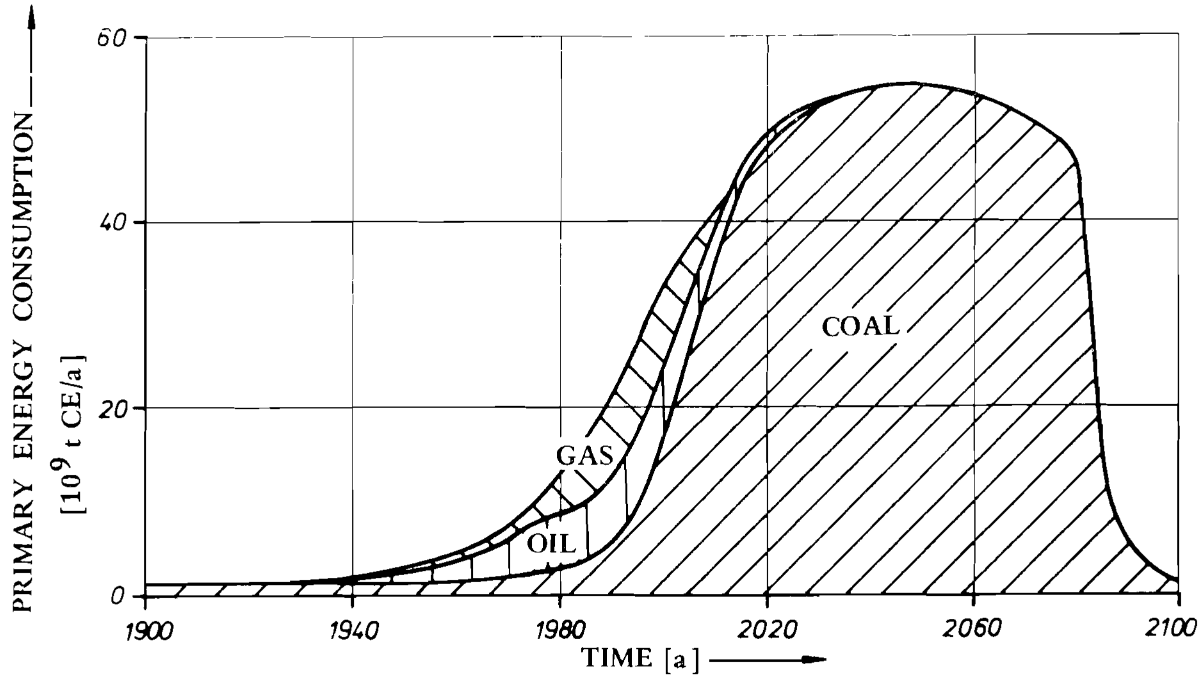

Figure 14. Development of primary energy consumption considering no nuclear energy.

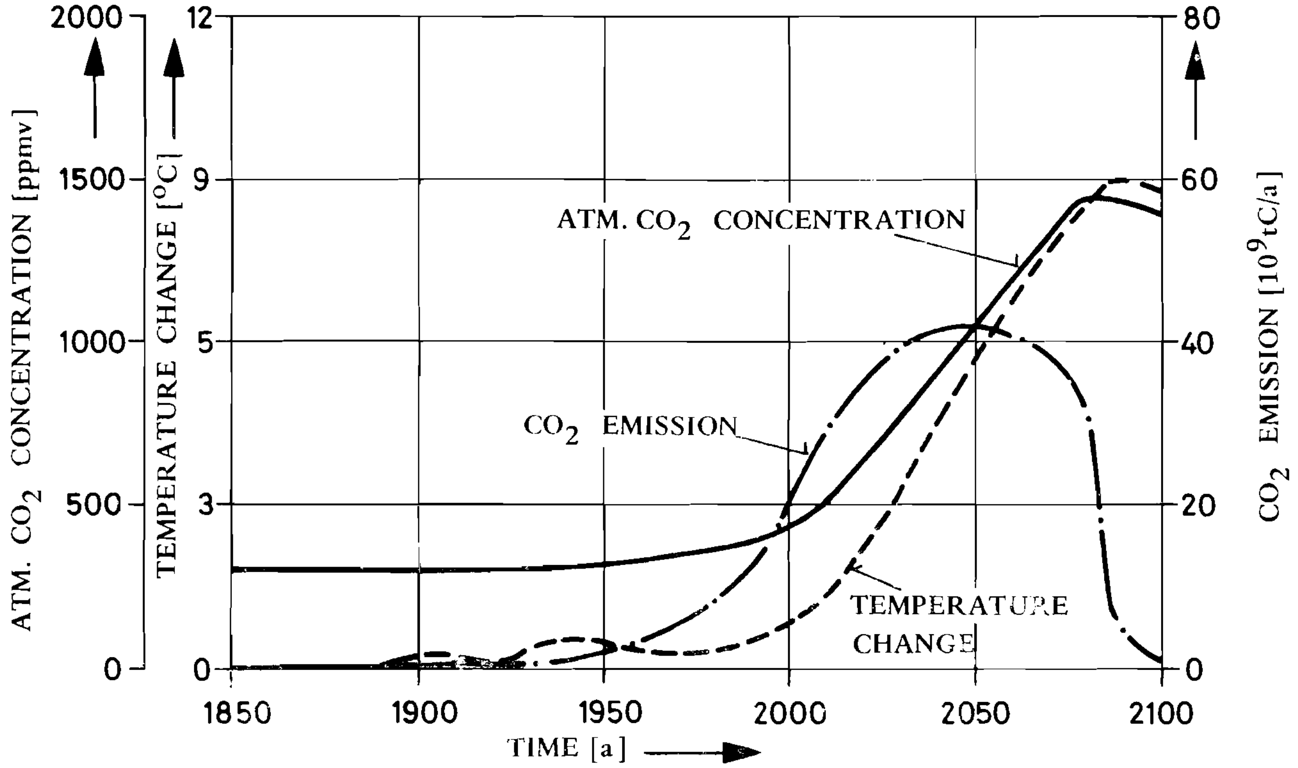

Figure 15. Simulation of the future CO_2 burden to the atmosphere considering no nuclear energy.

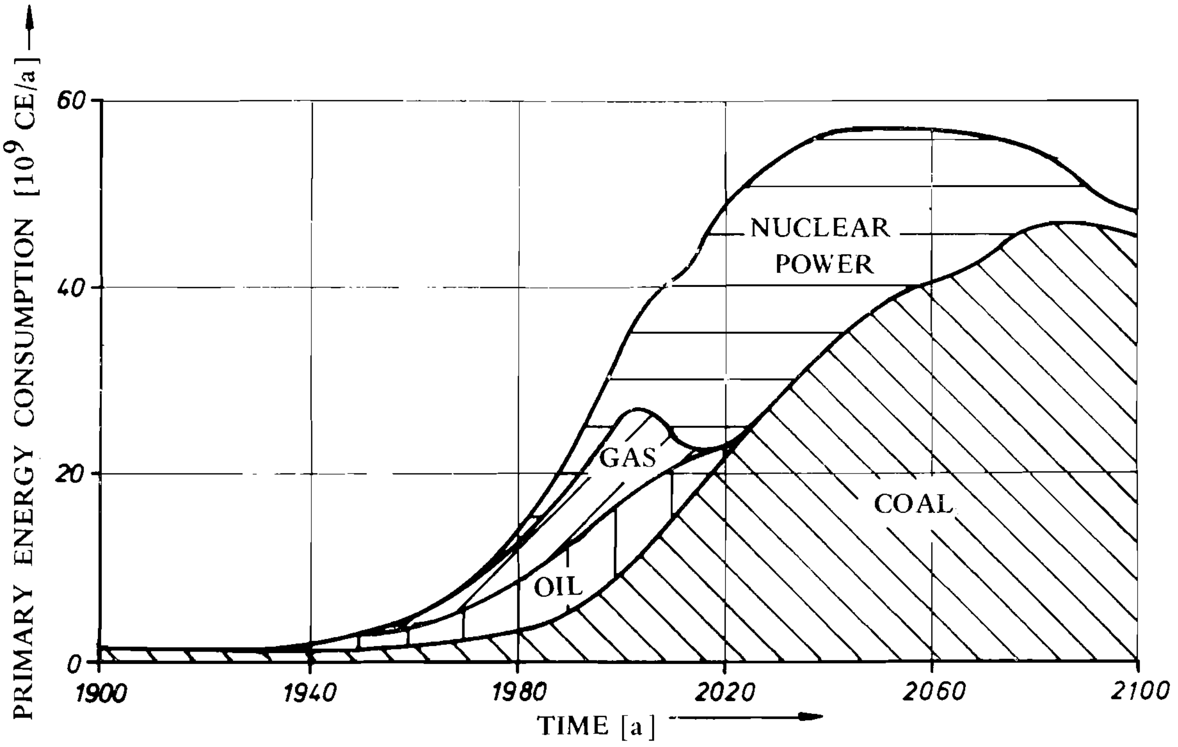

Figure 16. Development of primary energy consumption considering LWR's.

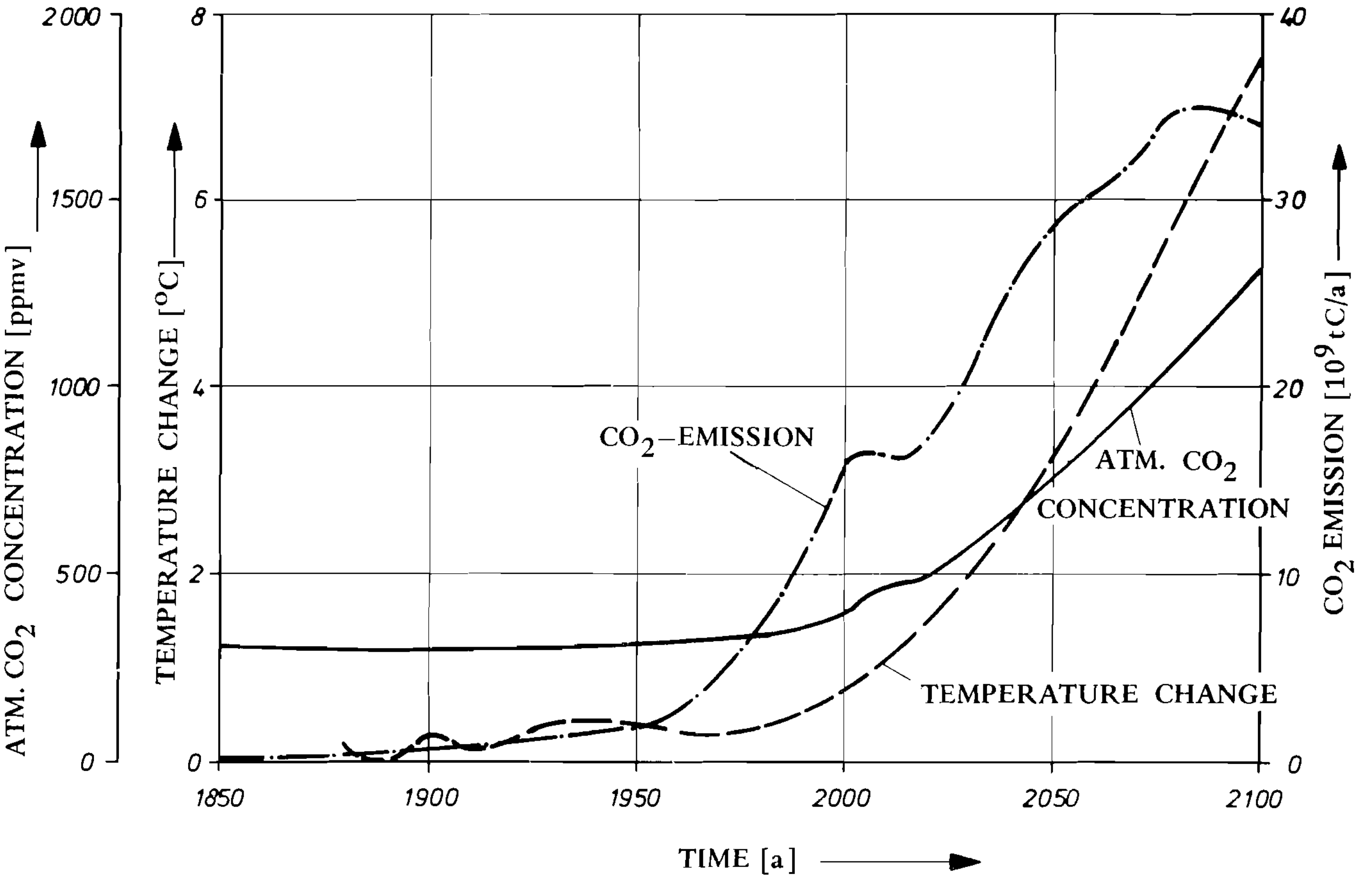

Figure 17. Simulation of the future CO_2 burden to the atmosphere considering LWR's.

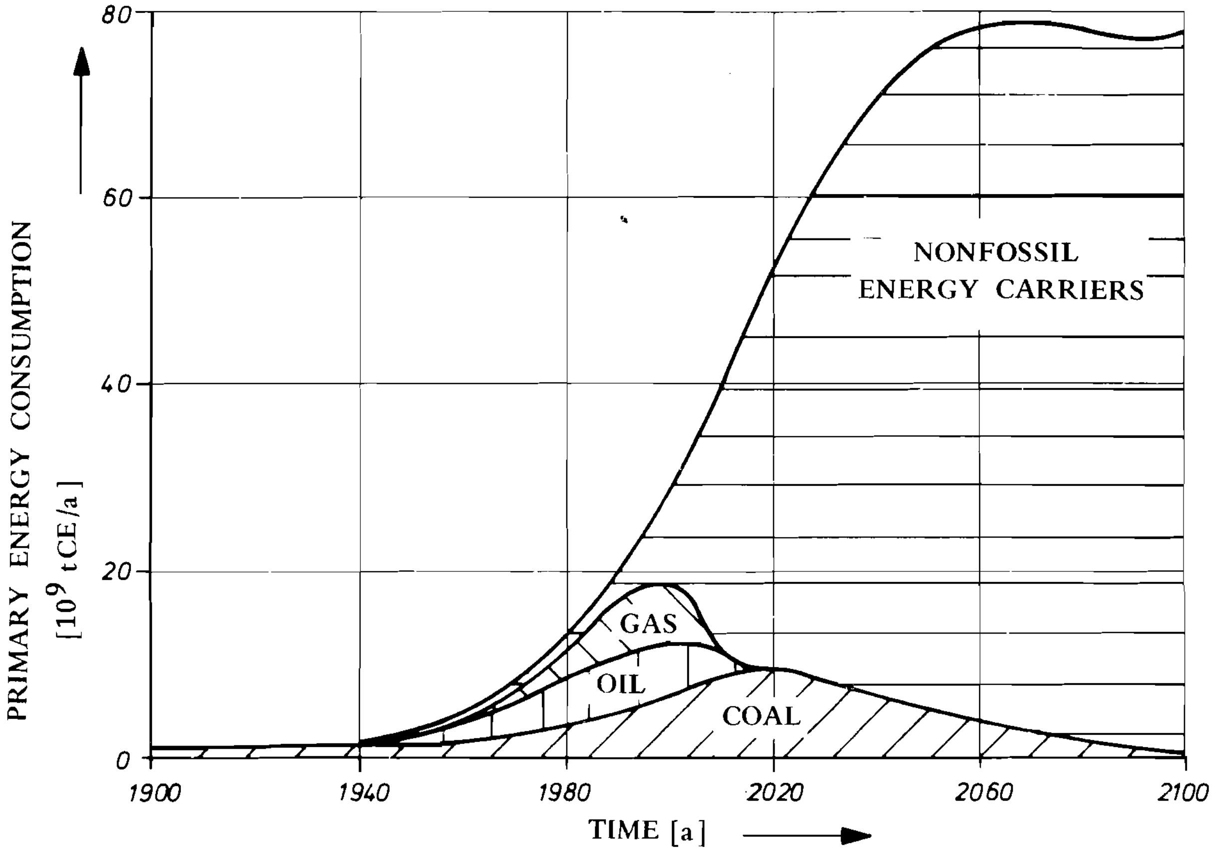

Figure 18. Development of primary energy consumption with regard to CO_2 emission reduction.

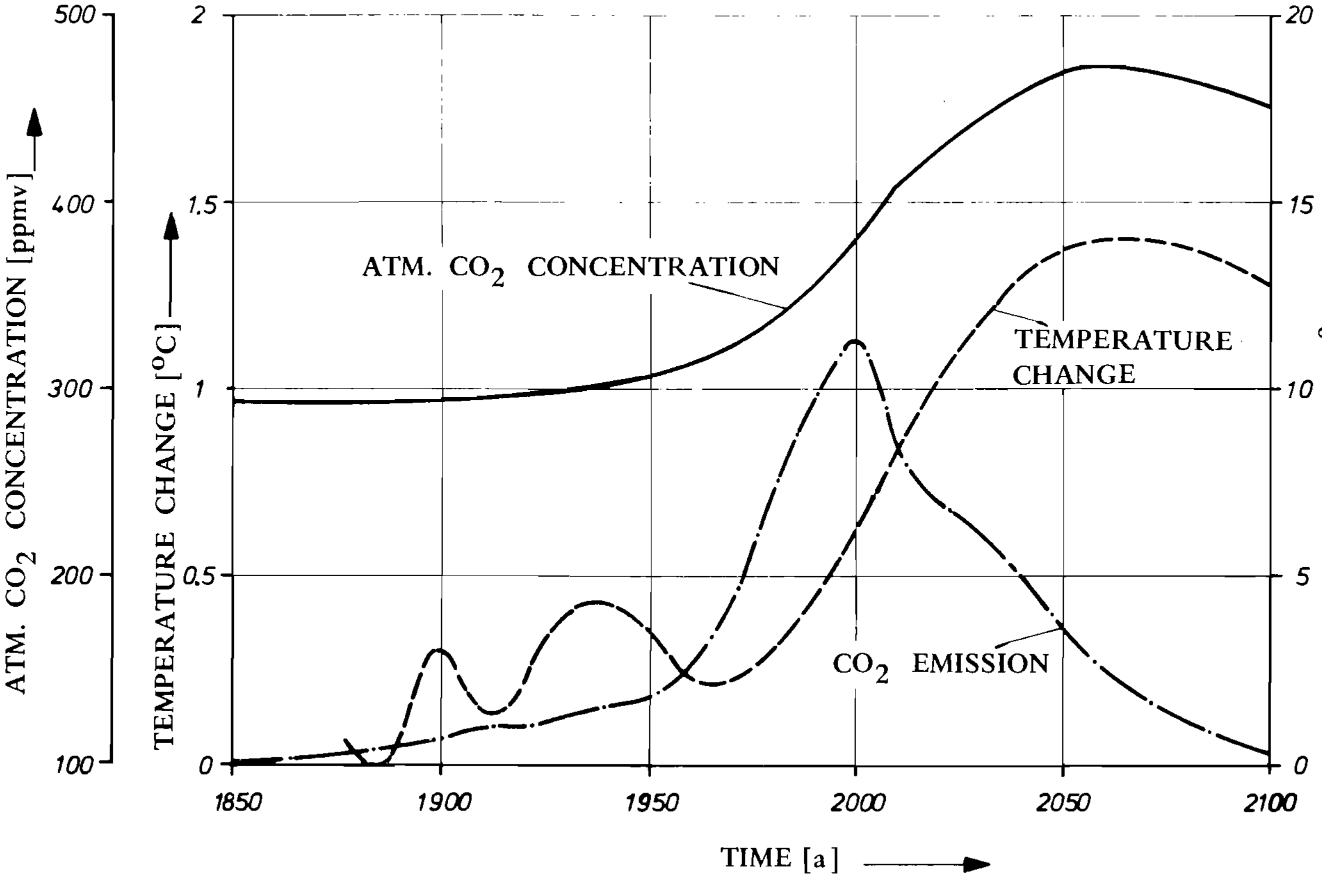

Figure 19. Simulation of the future CO_2 burden to the atmosphere with regard to a CO_2 emission reduction strategy.

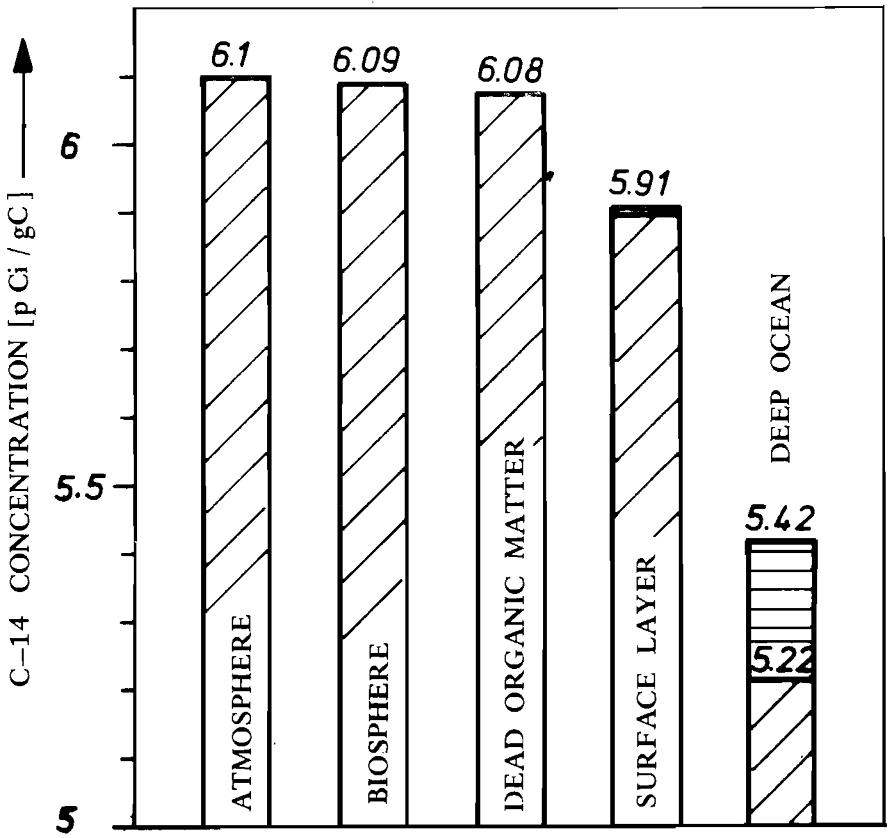

Figure 20. C–14 concentrations of various levels as calculated by the model.

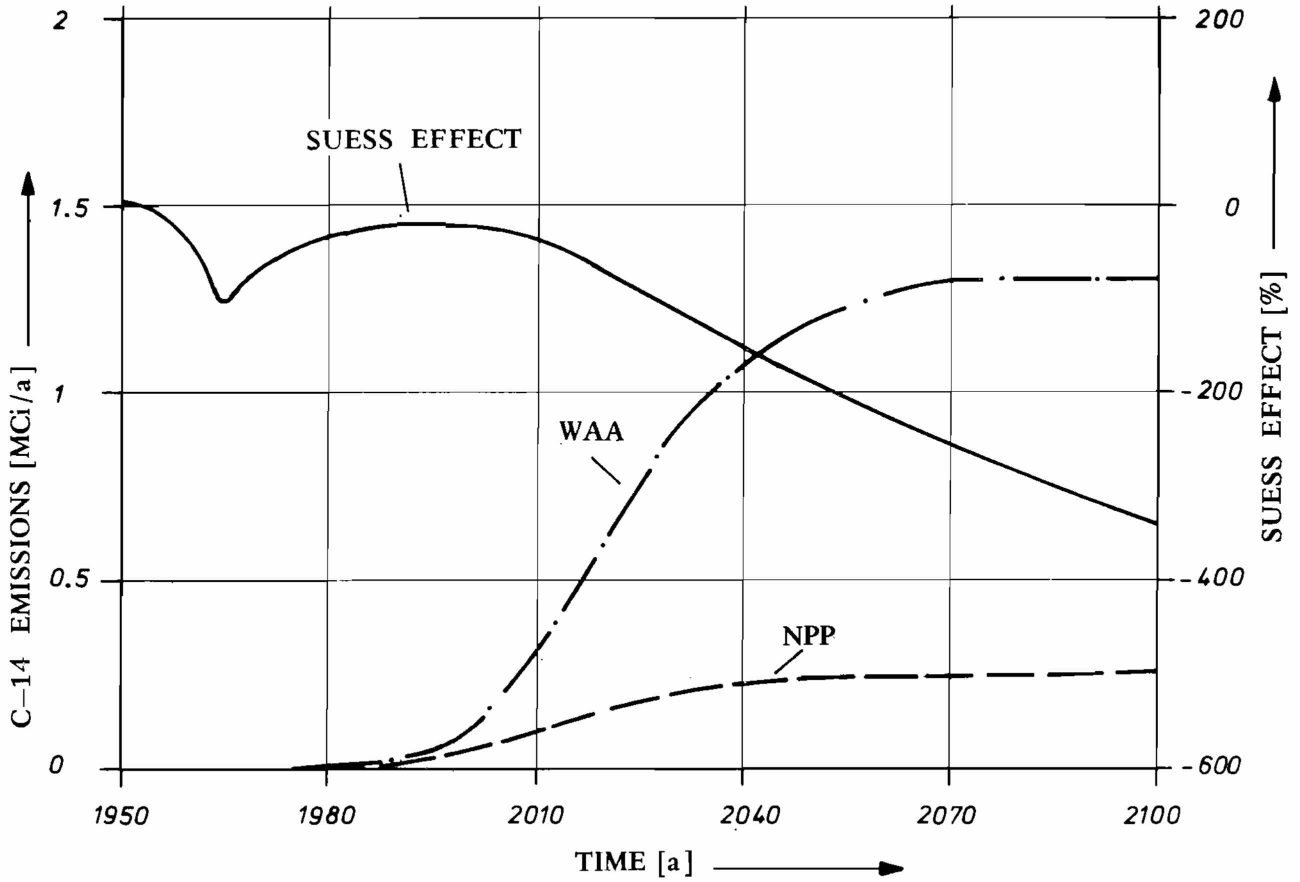

Figure 21. C–14 emissions and Suess effect according to consumption rates as given by Figure 10.

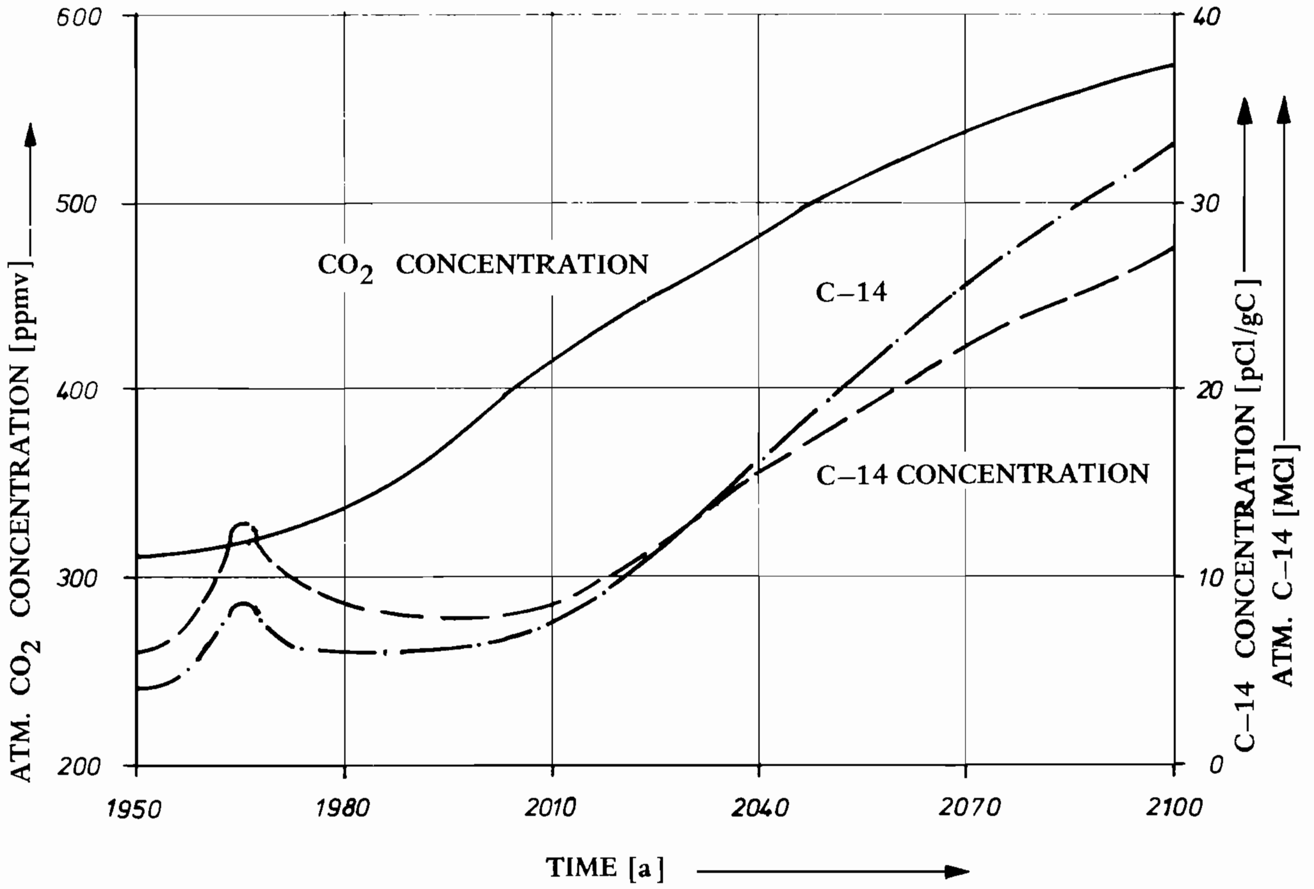

Figure 22. Development of the C–14 content and the C–14 concentration of the atmosphere.

Table 1. Specific CO_2 emission factors.

Energy Carrier	Heating Value {kcal/kg}	Carbon Content {%} (by mass)	CO_2-Emission Factor {tCO_2/tCE}	CO_2-Emission Index Nat. Gas = 100
Lignite (FRG)	2000	26.3	3.38	180
Bituminous Coal	7000	75	2.75	146
Oil	10000	86	2.19	116
Natural Gas[1]	9550	70	1.88	100
Methan	11980	75	1.63 4.03[2] 2.93[3]	87 215[2] 156[3]

[1] Compounds: 80% CH_4 + 15% C_2H_6 + 5% N_2
taking into account emission of gasification

[2] Autothermal: 1 t coal → 1030 Nm^3 CO_2 + 700 Nm^3 CH_4

[3] Allothermal: 1 t coal → 700 Nm^3 CO_2 + 880 Nm^3 CH_4

Table 2. C–14 emissions due to nuclear explosives [36].

Year	Emission {10^3 Ci}
1945 - 51	15
1952 - 54	1200
1955 - 56	560
1957 - 58	1700
1959 - 60	0
1961	2400
1962	4330
Total	~ 10200

Table 3. C–14 emission factors of nuclear power plants and reprocessing facilities (RP) (38) $\{Ci/1000\ MW_e \cdot a\}$.

Reactortype	Emitted			Disposed
	Reactor	RP	total	
PWR	11.0	15,5	26.5	3.9
BWR	11.2	18.3	29.5	3
HTR (pebble bed)	3.5×10^{-5}	81.8	81.8	-
HTR (block)	3×10^{-4}	76.1	76.1	-
NaSR (loop)	20	2.1	22.1	14.4

References

(1) Otway, H.J. and Pahner, P.D. Risk Assessment. Futures, Vol. 8, Nr. 2, pp. 122-134, April, 1976.

(2) Forrester, J. Industrial Dynamics. MIT Press, Cambridge, Massachusetts, 1961.

(3) Niehaus, F. Langzeitaspekte der Umweltbelastung durch Energieerzeugung: CO_2 und H^3. Report of the Nuclear Research Center Juelich, Juel-1165, 1975.

(4) Manabe, S., et al. Thermal Equilibrium of the Atmosphere with a Given Distribution of Relative Humidity. Journal of Atmospheric Sciences, Vol. 24, Nr. 3, pp. 241-259, 1967.

(5) Manabe, S. Estimates of Future Change of Climate Due to the Increase of Carbon Dioxide Concentration in the Air; W. Matthews, et al. Man's Impact on the Climate. MIT Press, Cambirge, Massachusetts, pp. 249-264, 1971.

(6) Broecker, W. Climatic Change: Are We on the Brink of a Pronounced Global Warming? Science, Vol. 189, pp. 460-463, August, 1975.

(7) Keeling, Ch. Industrial Production of Carbon Dioxide from Fossil Fuels and Limestone. Tellus, 25, Nr. 2, pp. 174-198, 1973.

(8) Report of the Study of Critical Environmental Problems (SCEP), Man's Impact on the Global Environment. MIT Press, Cambridge, Massachusetts, 1970.

(9) Stålfelt, M. Die Frage der begrenzenden Faktoren (Allgemeines). Das Zusammenwirken der aeusseren und inneren Faktoren. From Ruhland, W. Handbuch der Pflanzenphysiologie. Bd. 5, 1 und 2, Die CO_2-Assimilation. Springer Verlag, Berlin, pp. 213-225, 1960.

(10) Nielsen, E. Uptake of CO_2 by the Plant. From Ruhland, W. 9, 1, pp. 70-84, 1960.

(11) Ståfelt. M. Das Kohlendioxyd. From Ruhland, W. 9, 2, pp. 81-99, 1960.

(12) Ståfelt, M. Temperatur. From Ruhland, W. 9, 2, pp. 100-105, 1960.

(13) Koch, W. Untersuchungen ueber die Wirkung von CO_2 auf die Photosynthese einiger Holzgewaechse unter Laboratoriumsbedingungen. Flora, Abt. B, Bd. 158, pp. 402-428, 1969.

(14) Kanwisher, J. PCO_2 in Sea Water and its Effect on the Movement of CO_2 in Nature. *Tellus*, 12, No. 2, pp. 209-215, 1960.

(15) Robinson, E., et al. Concentration and Fate of Gaseous Atmospheric Pollutants. From Strauss W. Air Pollution Control. Part II, Wiley-Interscience, New York, pp. 1-88, 1972.

(16) Budyko, M. The Efffect of Solar Radiation Variation on the Climate of the Earth. *Tellus*, 21, No. 5, pp. 611-619, 1969.

(17) Mitchell, J. A Preliminary Evaluation of Atmospheric Pollution as a Cause of the Global Temperature Fluctuation of the Past Century. From Singer, F. Global Effects of Environmental Pollution, Reichel, D., Holland, pp. 139-155, 1970.

(18) Walton, A. Carbon-14 Concentrations in the Atmosphere and Carbon Dioxide Exchange Rates. *Journal of Geophysical Research*, Vol. 75, No. 15, pp. 3089-3098, 1970.

(19) Young, J. et al. Radiocarbon from Nuclear Weapons Tests. *Journal of Geophysical Research*, Vol. 73, No. 4, pp. 118-1200, 1968.

(20) Voss, A. Ansaetze zur Gesamtanalyse des Systems Mensch - Energie - Umwelt. Report of the Nuclear Research Centre Juelich, Juel-982-RG, 1973.

(21) Ehrlich, P., et al. Bevoelkerungswachstum und Umweltkrise. Fischer Verlag, 1972.

(22) Cloud, P. Wovon koennen wir morgen leben? Carl Haeuser Verlag, Muenchen, 1971.

(23) Meadows, D., et al. The Limits to Growth. Universe Books, New York, 1972.

(24) Meadows, D., et al. The Dynamics of Growth in a Finite World. A Technical Report on the Global Simulation Model World 3, 1973.

(25) Bolin, B. The Carbon Cycle. Scientific American, pp. 125-132, 1970

(26) Oeschger, H. A Box Diffusion Model to Study the Carbon Dioxide Exchange in Nature. Tellus, 27, 1975.

(27) Mordy, W. Bedroht Energie-Erzeugung das Klima? From Probleme im Gespraech, Verlag Land, Bern, pp.103-112, 1973.

(28) Flohn, H. Personal Communication. Meteorological Institute, University of Bonn, FRG.

(29) Moeller, F. Personal Communication. Meteorological Institute, University of Munich, FRG.

(30) Kaplan, L. The Influence of Carbon Dioxide Variations on the Atmospheric Heat Balance. Tellus, 12, No. 2, pp. 204-208, 1960.

(31) Plass, G. The Influence of the Combustion of Fossile Fuels on the Climate. From Bockris, J. Electrochemistry of Cleaner Environments. Plenum Press, New York, London, pp. 24-46, 1972.

(32) Nordhaus, W. Can We Control Carbon Dioxide? IIASA WP-75-63, Laxenburg, Austria, International Institute for Applied Systems Analysis, 1975.

(33) Vogt, H. Die naechste Eiszeit - unsere Schuld? Der Kosmos, pp. 23-26, January, 1973.

(34) United Nations. Ionizing Radiations Levels and Effects. New York, 1972.

(35) Foster, R. Sources and Inventory of Radioactivity in the Aquatic Environment. BNWL-SA-4614, 1973.

(36) Bonka, H. Personal Communication. Institute for Reactor Technology, Technical University, Aachen, FRG, 1975.

(37) Pannetier, R. Nuisance du Krypton-85 Atmospherique. CEA-CONF-1150, p. 11, 1970.

(38) Bonka, H. Presentation: Reaktortagung 1974, Berichtband p. 404, Deutsches Atomforum, FRG, 1974.