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Avenhaus, R. and Häfele, W.

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Systems Aspects of Environmental Accountability*

Rudolf Avenhaus and Wolf Häfele**

Abstract

Human activities have increased in such a way that there now exists the danger that some global balances will be disturbed. As a result, there is today a widespread effort to get precise knowledge about these balances themselves as well as about the consequences of possible disturbances in these balances. Because of their magnitude these problems are inter-related with other problems. Additionally, effects which were considered earlier to be side effects become important. All this means that for the treatment of these problems a systems approach seems necessary.

This paper recommends use of the general concept of material accountability for the analysis and treatment of these problems. This has already been proposed by different groups. The reason it is emphasized here is that the material accountability concept has proven extremely valuable in the establishment of the IAEA safeguards system for nuclear material in the peaceful nuclear industry. It is especially the organization of this system in the plant operator's responsibility (generation and reporting of source data for material balance) and in the safeguards authority's responsibility (verification of these data by means of independent measurements) which allowed the acceptance of this system on a broad international scale and which GROSSO MODO could serve as an example for any future global monitoring system.

In the first part of this paper examples for balances existing in nature are given: oxygen, carbon dioxide, radiation balance of the earth atmosphere system. Models for these balances and their disturbances as well as the respective measurements are reported.

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In the second part we have tried to explain why the treatment of these problems necessarily leads into the field of systems analysis. Special reference is made to the problems outlined in this paper.

As an example for this kind of approach and for an existing global control system, the IAEA safeguards system and the mathematical models developed in the course of establishing that system are sketched in the third part.

In the fourth part, the economic implications of material accountability are described using the input-output approach; for the example of sulphur it is demonstrated in which way the consequences of constraints--e.g. in the form of emission standards--can be analyzed.

The paper ends with a schematic representation of the complex interrelations between the basic concepts: material accountability, verification by means of measurements, and economic implications.

Introduction

In earlier times the influence of man on his natural environment was not of great importance. Either all materials taken from the environment and used were given back again without further consequences--this was the case for example in a purely agricultural society--or the amounts taken were so small that they could be disregarded. For example, up to 1870 practically the only primary energy source was the combustion of wood. As demonstrated by the fact that after 1870 coal was used on a large scale, the amounts of primary energy needed increased in such a way that there was no longer a complete recycling of material; however, the amounts in question still were small. Of course, in earlier times also there were examples of human activities which caused irreversible changes (e.g. the erosion of complete landscapes as a consequence of uncontrolled deforestation, or the exhaustion of ore mines). However, in these cases the consequences were at most of regional extent. Only in recent times have human activities developed in such a way that their influence on the environment perhaps will cause irreversible changes of global extent.

The general problem of possible irreversible global changes of the environment, as well as the question of what could be achieved in this connection, shall be detailed here for examples of material balances existing in nature which man will disturb, namely the oxygen and carbon dioxide balance as well as the radiation balance of the earth atmosphere system. These problems are well known. The point to be made here is that they have grown in such a way that their interrelations with other problems as well as their effects which were considered earlier to be side effects become most important. As a result, they can no longer be treated in an isolated, discipline-oriented way--the application of systems analysis becomes necessary.

One of the tools which could prove useful in this connection is material accountability in a very general form. Several groups have already proposed this. Kneese and coworkers promoted the idea mainly in connection with the problem of waste disposal in industrialized societies [1]. In Ref. [2], environmental balances are proposed at the background of the experience with a global and functioning control system which is based mainly on material accountability: the IAEA safeguards system for nuclear material used in the peaceful sector of nuclear industry. Because of the importance of this system for all further developments, we will describe its relevant features.

This paper intends to demonstrate in which way the principle of material accountability which has proven so successful in the case of nuclear material safeguards could be applied to environmental pollution problems of local, regional, and international scale.

Material Balance Examples in Nature and the Influence of Man on These Material Balances

The oxygen and carbon dioxide cycle in nature not influenced by man has the following form: during the day a high rate of photosynthesis leads to the net production of O_2 and net consumption of CO_2. At night, with photosynthesis inactive, a net consumption of O_2 and production of CO_2 takes place. However, there is an overall net input of CO_2 and net output of O_2. The O_2 and CO_2 balances are closed if one takes into account the rotting of dead plants. In case of complete mineralisation of the plant mass, the total O_2 produced is consumed again and the total CO_2 consumed is put back into the atmosphere. Some people assume that the O_2 inventory of the atmosphere as a whole results from the formation of fossil fuels, i.e. from plant masses not completely rotted.

In a modern agricultural society there still is a net production of oxygen. On agricultural land in the FRG, an average of 10 t O_2 per hectare and year are produced and 3.5 t O_2 are consumed (animals, man, work, fuels). Thus a net output of 6.5 t O_2 per hectare and year remains [3]. However, if one considers the FRG as a whole, then one arrives at a O_2 production of 200 million t per year, and a consumption of 700 million t (of which 600 million t is used for the combustion of fossil fuels). Therefore, a deficit of 500 million t O_2 per year remains. Even if this holds only for a highly industrialized country, one may ask if we consume the oxygen of the atmosphere. We will come back to this point later.

Together with the combustion of the fossil fuel goes a carbon dioxide production of an enormous magnitude. In 1960, 10.8 billion t CO_2 were released all over the world into the atmosphere. This has already resulted in a measureable increase of the CO_2 content of the atmosphere. Measurements in Hawaii (i.e. which is located far from local CO_2 sources) indicate that the CO_2 seems to have been increasing throughout the world about 0.2 per cent per year, or 0.7 ppm out of 320 ppm [4]. To be able to ask what consequences this may have, one has to consider the CO_2 cycle in nature.

Consider Figure 1 (taken from [5]). On land CO_2 is taken up by vegetation and stored in plants and humus. The magnitude of this reservoir is similar to that of the atmosphere, and the exchange time is probably on the order of 30 to 40 years. The ocean provides a much larger reservoir and has the potential of storing some 60 times as much CO_2 as the atmosphere. The upper layers of the sea (above the thermocline) must, however, be distinguished from the deeper layers of the ocean. The upper layers are well mixed, and are in contact with the atmosphere, but they can hold only about as much CO_2 as exists in the atmosphere. Studies of the concentration of C_{14}, which is produced by cosmic rays in the atmosphere and subsequently decays to C_{12}, suggest that the rate of transfer of CO_2 from the atmosphere to the upper layers of the ocean is such as to require some 5 to 10 years for the transfer of a quantity equivalent to that in the atmosphere. Transfer to the deep ocean from the upper layers is a slower process, and as a result it would probably be a matter of centuries before the deep ocean reached equilibrium with any new level of concentration in the atmosphere.

It is estimated that at present about half of the amount of CO_2 released to the atmosphere by burning fossil fuels is kept in the atmosphere. Thus the question arises where the rest remains and what the consequences of this storage may be, and additionally, what the consequences of the increase of the CO_2 content of the atmosphere may be. For this purpose models must be developed (and have been developed) and tested by global monitoring systems. Models for the CO_2 balance of the earth are being developed, e.g. by Fairhall and by Zimen [6]. They state that the CO_2 will be stored in the sea and there possibly could cause intolerable disturbances of the ecological system of the sea. Many models on the other hand state that the increased CO_2 content of the atmosphere changes the radiation balance of the earth resulting in an increase of the average temperature of the earth (the so-called Greenhouse effect).

To explain this, in Figure 2 the radiation balance of the earth is shown [7]. The solar input above the atmosphere, averaged over day and night and all zones of the globe, is 340 W/m^2. Roughly 47% reaches the surface of the earth, that is, 160 W/m^2; the rest is absorbed within the atmosphere or is reflected immediately. Absorption of solar radiation within the atmosphere is by the various trace gases, principally water vapor, CO_2, O_3 and molecular oxygen, and by dust and haze. Additional absorption takes place within clouds by the liquid water droplets and ice crystals in the clouds. The right hand side of Figure 2 shows the radiation balance between atmosphere and earth: infrared radiation from the earth to the atmosphere and inversely, and heat losses of the earth by evaporation and convection. As early as 1863 Tyndall suggested that the blanketing effect of increased CO_2 would cause climatic changes through variation of the surface temperature. Increased CO_2, because of its strong absorption (and thereafter emission) of infrared radiation at 12 to 18μ would reradiate energy downward to the earth's surface and further inhibit the radiative cooling at the ground. As it is reported in Ref. [4], radiative equilibrium models, including a convective adjustment, suggest that the projected 18 per cent increase of the CO_2 concentration by the year 2000 would result in an increase of the surface temperature of about one-half degree and a stratospheric cooling of 0.5^{o} to $1^{o}C$ at 20 to 25 km. However, these models neglect the important interacting dynamics and thermodynamics of the atmosphere, as well as the ocean-atmosphere interaction. This neglect makes the computed temperature changes very uncertain.

Monitoring

We have given above examples of balances existing in nature, and mentioned disturbances by men of these balances, as well as the attempts to model these balances themselves and the consequences of man's disturbances of the balances. Now the problem arises to carry through appropriate measurements in order to verify (or falsify) these models.

In the case of oxygen, measurements have been performed since 1910. Intensive measurement during the years of 1967 to 1970 [8] showed that the oxygen content of the atmosphere has not changed within the accuracy of the measurements. These measurements had been proposed because there was the fear that in addition to the oxygen consumption caused by the combustion of fossil fuels, the herbicides and pesticides concentrated by the basic photosynthetic organisms could affect their population, thereby modifying the equilibrium concentration of oxygen in the earth's atmosphere. As stated before, this could not be verified by the measurements. There are also theories that the oxygen balance is regulated by completely different effects [9]. However, in view of the risk involved the study group for critical environmental problems has proposed to perform measurements with better accuracy at least every 10 years. The recommended sampling procedure of 10 years seems to have been chosen somewhat arbitrarily. The optimal design of environmental monitoring schedules, both in space and time, would seem to be a legitimate topic for research through the methods of applied systems analysis.

In the case of the CO_2 system of the earth, it has been proposed to measure the three interacting systems of source, route, and reservoir. As already mentioned, sources are the combustion of fossil fuel and the release and take up of CO_2 by the oceans. In the latter case observations have already been made in the three areas where there is a strong exchange between deep and surface water: the Northern North Atlantic, the far North-West Pacific, the Weddell Sea. Routes are being observed by aerial measurements. Global averages are measured, e.g. in Hawaii. It has already been proposed to have at least four observation stations on the earth, far from local sources. Cost estimates have been made for a "sufficiently" dense (in time and space) global monitoring system. Here, the same comment holds as for the situation in the preceding paragraph.

For study of the radiation balance of the earth--contrary to the case of oxygen and carbon dioxide--satellite observations make a unique contribution to the understanding of atmospheric energetics. Apart from their use as important atmospheric probes, satellites provide us with direct observations on a global and relative real-time scale of the distribution of various radiation parameters at the upper boundary of the atmosphere. Accurate satellite measurements can provide global distributions of the earth-atmosphere albedo as well as the absorption, emission, and net radiation balance of the overall earth plus atmosphere system [10].

Systems Problems

The problems sketched above are well known. There already exists a broad literature on the problems themselves as well as on the respective measures taken up to now, and some references have been given. More emphasis, however, should be laid on the two following aspects:

1) The degree of risk involved must be estimated, and the measures taken at least for recognizing, but also for reducing, must be seen in view of this risk. Risk evaluation represents one of the most important problems for systems analysis. An example where this procedure is already followed is the nuclear power

plant: Here, one has to guarantee extremely high technical reliability rates in view of the risk of a potentially large accident.

2) The degree of interdependence of different problems. It is no longer possible to study the problems in an isolated manner; all different and interweaving aspects have to be considered at the same time. An example for this is the situation of today's air traffic. It is no longer a problem of the aeroplanes themselves which work well and therefore are no longer subject of large scale development. It is rather the problem of the organisation of the air traffic, the transportation to and from the aeroplanes, the risk of hijacking, etc., which are the subject of most concern. An example in the context here has already been given: the interdependence of the CO_2 cycle and the radiation balance of the earth-atmosphere-system.

As a consequence of these deliberations one has to tackle these problems from a systems point of view. This means that it is necessary to identify and to understand all systems problems that are inherent in the various options for large scale human activities. This will be a continuing task and will probably never be completed as human activities expand further and further. This task is not a matter of algorithms. It is rather a matter of technological and sociological substance. It is particularly important to identify the various interweavings that become dominating with the increasing sum of human activities. To some degree this requires disciplinary-oriented work but only to the extent that is necessary for identifying the discipline-oriented questions. From then on it is the task of the various scientific disciplines to pursue the questions thus identified in connection with systems analysis. Finally, it will be necessary to identify and evaluate alternatives and to minimize the systems problems. This leads into severe methodological problems; key words here are "vector-valued optimization" and "decision under uncertainty."

Specifically in the case of environmental pollution the following steps must be taken once the goal of any control has been agreed upon:

1) Identification of ecologically meaningful parameters for monitoring. Here the ecologists should have the central conceptual role.
2) Identification of control points in environmental systems.
3) Identification of realistic control strategies from the administrative and political side.

One possible tool for the analysis and treatment of material balance problems in view of the aspects mentioned above is the concept of material accountability. This concept is of special interest in the cases sketched, with special attention to the following two steps:

1) Establishment of the relevant material balances. This means, for example, the development of appropriate models.
2) Verification or monitoring of these balances with the help of independent measurements.

Steps in this direction for the problems sketched above have already been taken. In the case of oxygen, for example, models of the possible consumption are made, and inventory measurements are then carried out. Additionally, periodic measurements are proposed to be taken in the future, but only every ten years as the danger is estimated to be rather low still. More attention is paid to the CO_2 problem; many models have been developed, the necessity of a global monitoring system is stressed, and proposals concerning its network in time and space are being made. Even the problem facing decision makers to look for alternatives for the combustion of fossil fuels is discussed in view of the possible danger of too high a CO_2 content in the atmosphere. The situation is similar for the radiation balance of the earth.

It must be emphasized that up to now the models are incomplete and, furthermore, that there are no real global monitoring systems. Although proposals in this direction have been made great obstacles still seem to exist. In this connection it is important to note that a functioning global monitoring system for the control of a specific substance does exist already--the IAEA international safeguards system, which is based mainly on the concept of material accountancy. As this system in many respects could serve as an example of possibilities which today already exist, we shall sketch its relevant features in the following.

The IAEA Safeguards System

After ratification by forty-three states, the Non-Proliferation Treaty for nuclear weapons came into force on March 5, 1970. This treaty, which had been inaugurated by three states--the UK, USA, and USSR--and signed on July 7, 1968, aims to prevent other states from obtaining nuclear weapons. The treaty foresees international controls which shall guarantee that a diversion of nuclear material from the peaceful sector of the fuel cycle is detected in time. These controls shall be carried out by the International Atomic Energy Agency in Vienna.

Although at the time the treaty was inaugurated, nuclear plants of the various kinds had been operated for 25 years--and connected with it, experience in the control of nuclear material had been gained--it was clear from the beginning that international safeguards of national fuel cycles would create entirely new problems. Therefore from the very beginning an effort has been made to develop and analyze the safeguards procedures from a systems point of view.

This world-wide effort culminated in the work of the so-called safeguards committee which had been established by the board of governors of the IAEA and in which more than forty states were represented. This committee worked intermittently from July 1970 to February 1971, creating a model for the agreements to be worked out between the IAEA and the states [11]. In this model all relevant aspects and procedures of the safeguards system are laid down.

The three basic measures of the IAEA safeguards system are:

a) Material accountability
b) Containment
c) Surveillance.

The first of these measures has been recognized to be a measure of fundamental importance, the other two being important complementary measures. As material accountancy is of special interest in the context of this paper it will be considered exclusively in the following.

The first step in the establishment of a material accountability system on a plant level is to define an area--which may or may not coincide with geographical boundaries of a plant-- for which a) the quantity of nuclear material in each transfer into or out of the area can be determined, and b) the physical inventory can be determined when necessary. For this material balance area (MBA) key measurement points

(KMP) must be defined where the flow or inventory of nuclear material may be measured in an appropriate way.

Once the quantity of material in a MBA is determined a book inventory may be maintained by recording measured flows into and out of the area at the appropriate KMP's. At the end of an inventory period a physical inventory is taken; the correspondence between the nuclear material contents of the MBA as written down and in fact is the basis for judging whether or not any material is unaccounted for (see Fig.3). There are many reasons for a non-zero difference between book and physical inventory: hidden inventories, unmeasured losses, measurement uncertainties, and diversion. Therefore, statistical techniques must be applied in order to judge whether or not a difference is significant for a potential diversion.

This formalism can be and is applied to a variety of situations. Different approaches have been developed for reactors, stores, manufacturing , reprocessing, and enrichment plants, etc. Whereas the formalism is simple in the case of a single MBA and a single inventory period, it becomes complicated if one tries to interlink different inventory periods or different MBA's in a country with an advanced fuel cycle.

However, what is even more important for the IAEA international safeguards system which is now functioning is the fact that this MBA formalism could be internationally accepted, as it has been. Additionally, this formalism provided the basis for all safeguards studies, both in selection of how safeguards were to be applied and, for example, future manpower requirements for verification.

The IAEA safeguards system as it is organized now consists of three elements:

First, requirements for the operator of a plant are defined which form the basis of the safeguards system, i.e.

-definition of MBA's

-establishment of a system of measurement or other determination of nuclear material contents

-keeping of appropriate records for materials accountability chosing of materials balances by taking physical inventories and evaluation of MUF, hidden inventories and losses.

Second, the national or regional safeguards authority submits the information to the IAEA. This information includes those features of the design of a nuclear plant which are relevant to safeguards application; in particular, it includes data on all inventory changes in all MBA's and all physical inventory takings. This world-wide reporting of material data is now established and functioning. The national or regional authority may or may not have its own independent verification function.

Third, this information is verified through inspections by authorized IAEA inspectors. Here, the question of inspection effort becomes a central problem.

The way this safeguards system should be and the way in which it was analyzed are described in Ref. [12]; only some essential features shall be reported here.

First, there was the question of the very objective of safeguards. After long discussions it was agreed that it is

> ...the timely detection of significant quantities of nuclear material from peaceful nuclear activities... and deterrence of such diversion by the risk of early detection. [11]

Thus, the objective was not to prevent the plant operators from misusing the plant for processing undeclared material--which could not be achieved with a limited safeguards effort.

Second, there was the problem of balancing the objectives against the technical and economical possibilities. Should the inspector look for mg, g or kg of nuclear material possibly diverted? An example of this situation for the case of one inventory period is given in Figure 4. It can be seen that if one wants to detect a diversion of 3 kg the measurement accuracies expressed by σ only allow for a probability of detection of 20%, assuming a false alarm rate of 5%. Here it must be stressed that it was not possible to come to such conclusions only by means of theoretical analyses. A major effort was made by the so-called <u>integral experiments</u> where the underlying problems (losses, measurement performance, etc.) could be identified and where the necessary data were obtained (see e.g. [13]).

Third, the question of optimal distribution of inspection effort arose. An example of the analyses performed here is given in Figure 5 where a model fuel cycle was constructed and analyzed [14]. Taking into account the various possibilities of the plant operator to divert material one was led into game theoretical considerations [15].

As a last point we should mention that internationality required that the system should have boundary conditions: the system should be

-objective
-rational
-formalized.

It is the general opinion now that the safeguards scheme sketched above fulfills the second and the third postulate. In order to explain what degree of objectivity is reached up to now the underlying mathematical model is sketched in the following part.

Before this, in concluding the description of the IAEA safeguards system one may say that it has proven workable for all parties involved: the plant operators, the states, and the safeguards authority. Therefore, it is natural to ask if this experience could not be used in similar cases. Environmental pollution control, for example, seems to be such a case as can be seen from the preceding chapter.

Up to now there exist no working examples in the form of cases where the safeguards experience has been used directly, even though there are ideas to establish a similar safeguards system for the control of the oil spills on the Rhine which seem to be major problem. Here one could introduce a similar accountability system for the motor oil. The organization scheme particularly could be copied directly: records kept by the ship captains, verification of the records by an independent authority.

Mathematical Model for Material Accountability

Consider the case of one nuclear plant (or one ship, or one oil fired power plant--see next section) where there exists the risk for material to disappear. According to Figure 3 the establishment of a material balance for the time interval (t_o, t_1) means the evaluation of the "Material Unaccounted For" (MUF) at time t_1

$$\begin{aligned} MUF &= BI - PI_1 \\ &= PI_o + \Sigma R - \Sigma S - \Sigma D - PI_1 \quad . \end{aligned} \tag{1}$$

Here, PI_o and PI_1 are the physical inventories at times t_o and t_1, and BI is the book inventory at time t_1.

In case no material will disappear (Null Hypothesis H_o), the expectation value of MUF is zero. In case the amount M will disappear in (t_o, t_1) (Alternative Hypothesis H_1), the expectation value of MUF is M:

$$E(MUF/H_o) = 0 \quad , \quad E(MUF/H_1) = M \quad . \tag{2}$$

Therefore, a significance test is made in order to check if H_o or H_1 is true. It is assumed that all measurements have normally distributed random errors. Then the probability of detection in case of disappearance of M is given by

$$1 - \beta := \text{prob}\{\text{MUF} > X/H_1\} = \phi(\frac{M}{\sigma} - U_{1-\alpha}) \quad , \qquad (3)$$

where X is the significance threshold, σ^2 is the variance of all measurement errors, α the false alarm probability, and U the inverse function of the Gaussian function ϕ. The value of σ^2 is fixed by the measurement system. Thus, $1-\beta$ is determined once M and α are given. The question arises how these quantities shall be determined. To answer this, let us go one step further.

Let T be the reference time in consideration (e.g. one year) and let this reference time contain n inventory periods. Furthermore, let $M = \Sigma M_i$ be the total amount disappearing during the n inventory periods. Then the total probability of detection will be

$$1 - \beta = 1 - \text{prob}\{\text{MUF}_1 \leq X_1 \wedge \cdots \wedge \text{MUF}_n \leq X_n/H_1\} \quad (4)$$

instead of (3).

As the random variables MUF_i, $i = 1,\ldots,n$, are dependent (because of the starting inventory), in general this expression cannot be written as a product of single inventory period probabilities. If one chooses, however, the starting inventory in a special form (i.e. as minimum variance unbiased estimate from book and ending physical inventory of the preceding inventory period) then one obtains from (4) corresponding to (3)

$$1 - \beta = \prod_{i=1}^{n} \phi\left(\frac{M_i}{\sigma_i} - U_{1-\alpha_i}\right) \quad , \qquad M_j, j = 1,\ldots,i \quad , \tag{5}$$

where M_i is a linear combination of all M_i, $i = 1,\ldots,n$. The overall false alarm probability α is then given by

$$1 - \alpha = \prod_{i=1}^{n} (1 - \alpha_i) \quad , \tag{6}$$

where α_i, $i,\ldots,n$, is the single false alarm probability of the i.th inventory period.

Let us assume that the overall false alarm probability α is given. Then the α_i should be chosen in such a way that the probability of detection $1 - \beta$ maximized

$$\max_{\alpha_i} (1 - \beta) = \max_{\alpha_i : \prod_i (1-\alpha_i) = 1-\alpha} \prod_i \phi\left(\frac{M_i}{\sigma_i} - U_{1-\alpha_i}\right) \quad . \tag{7}$$

This means that the single false alarm probabilities α_i are now determinants. If on the other hand a plant operator intends to divert the amount M during the reference time, he will distribute the single diversions in such a way that the probability of detection is minimized

$$\min_{M_i} \max_{\alpha_i} (1 - \beta) = \min_{M_i : \sum_i M_i = M} \quad \max_{\alpha_i : \prod_i (1-\alpha_i) = 1-\alpha} \quad \prod_i \phi\left(\frac{M_i}{\sigma_i} - U_{1-\alpha_i}\right) \quad , \tag{8}$$

Thus, the M_i also become determinants once M is determined. One could proceed further and determine by means of this optimization the values of M and α for the single plant after having fixed the corresponding values for a set of plants. However, it is clear that ultimately some values must be fixed in a more or less subjective way.

Once the material balance data are collected, the control authority has to verify these data with the help of independent measurements on a random sampling basis. This can be done, for example, by means of the D-statistics [16]. The problem of the optimal allocation of effort in case of different classes of material--game theoretical in nature--is analyzed in Ref. [17].

In the final evaluation of the whole system, all "strategies" of both the operator and the control authority must be taken into account. This means that the global probability of detection for the reference time (which includes n inventory periods and m D-statistics to be performed)

$$1 - \beta - 1 - \text{prob}\,\{MUF_1 \leq X_1 \Lambda \cdots \Lambda MUF_n \leq X_n \Lambda\, D_1 \leq X_{n+1}\, \Lambda \cdots \Lambda\, D_n \leq X_{n+m} / H_1\,\} \tag{9}$$

must be minimized with respect to the M_i, $i = 1, \ldots, n + m$, and maximized with respect to the X_i, and where the following boundary conditions are given

$$\overset{n+m}{\underset{i=1}{}} M_i = M \tag{10}$$

$$1 - \alpha = 1 - \text{prob}\,\{MUF_1 \le X_1 \wedge \cdots \wedge D_m \le X_{n+m} / H_0\} \quad . \tag{11}$$

As the MUF_i, $i = 1,\ldots,n$, and the D_i, $i = 1,\ldots,m$, are dependent (the original data are used for both the material balance establishment and the data verification), the expression (9) cannot be factorized and simulation seems to be the only tool for analysis.

Accountability in Economic Terms

The accountability measures in the nuclear industry may already be viewed as an example of accountability in the economic domain. In fact, even before the introduction of safeguards, accountability measures were carried out in the nuclear industry for economic and security reasons. The additional costs imposed on the nuclear industry by safeguards are low compared to the existing measures and costs.

Trends towards a similar accountability can be observed in other sectors of the industry; their form, however, is less explicit than that described in the last chapter. This is demonstrated by the fact that in cases where the transfer of important materials from one sector to the other is analyzed so-called input-output analyses have been introduced. In the specific form of the mass models, however, the concept of the closed material balance is absent because in all industrial processes waste is generated which is not included in the considerations.

In recent years different groups have made an effort (see e.g. [18], [19]) to study comprehensively by means of input-output analyses the flow of materials used by man. This procedure can be viewed as a formulation of the accountability idea in economic terms. We shall illustrate this below for a specific example.

Consider the case of an oil-fired power plant. Sulphur comes in with the oil and leaves the plant in form of SO_2 together with the offgases through the stack if there are no filters which trap the SO_2. If there are filters, then a certain percentage of the sulphur is removed from the offgas, however, it is kept in the filters and one has to ask where the sulphur goes from there. If an oil desulphurization is foreseen--which transforms a power plant into a chemical facility [20]--then the sulphur is kept in form of chemical compounds before the oil goes into the process, and one has to ask what happens to these chemical compounds. In any case it is important to observe the flow of the sulphur including the final deposition of the sulphur compounds removed from the offgas or from the oil. Otherwise, one would have kept the sulphur out of the air but sent it eventually in the form of chemical discards into the groundwater; in other words, one would not change the final effect.

It is obvious that the establishment of the material balance for sulphur in an oil-fired power plant is very similar to the case, for example, of the plutonium material balance in a reprocessing plant. Thus, in this context also integral experiments have already been proposed as according to Ref. [11]: "Our knowledge of the flow of materials through the economic system and their loss or purposeful discharge to the environment is extremely limited, especially with respect to the industry." The final element in verification of the material balance through inspections--so important in safeguards-- may at the present stage not be relevant to the discussion of pollutant accountability. Only if strict standards for the emission of pollutants are set up, which may impose an economical burden on the plant operators, the question of illegal release of pollutants and, therefore, of the verification of data, may become important.

Accountability of pollutants in a region poses completely different problems. Consider, for example, the air volume over a given region as a material balance area in the sense described earlier. To establish a material balance for the pollutants in this material balance area means to determine

a) the inputs over a given period of time (i.e. all the emissions into that volume);

b) the outputs over a given period of time (i.e. the removals by washing out by rainfalls, decays, etc.); and

c) the physical inventory at the beginning and at the end of an inventory period.

The inputs can be measured at least in cases where they come from point sources (e.g. facilities), they can be estimated to a fairly good degree in case they come from spread sources, e.g. from households or from transportation. The inventory can be measured by monitoring systems as they have been established in certain regions (Los Angeles, the Ruhr area, etc.). The outputs cannot be measured directly.

One may argue that the outputs can be evaluated over a certain period of time determining the difference between beginning inventory plus inputs minus ending inventory; however, that is not in the sense of the material balance as full knowledge of the processes involved can never be obtained. In the case of safeguards this is a well-known problem. In many cases waste has not been measured directly but determined "by difference" of measured throughput and physical inventory. Losses or diversion then can never be detected by definition.

To solve this problem in the case of environmental accountability one needs to establish models which describe the processes of formation and decay as well as washing out of pollutants in and from the atmosphere. Once such models have been fully established they can take the place of the missing "output" measurements. However, such models must be tested, and in principle they can only be tested if a complete measurement system is available. This problem can be solved only by an iterative process.

Models of the type postulated have been started already. In Table 1, which represents a summary from calculations performed in Ref. [21], results from a crude model for the Ruhr area are shown. They correspond in a satisfactory way to the results of measurements. More complex models are being established, e.g. for the Tennessee Valley Region [22], [23], where the chief emphasis is on radioactive discharge.

If one wants to get a complete picture of the flow of sulphur through an economy including the repercussions of standards or other constraints imposed, one has to establish the input-output matrices mentioned earlier. In Table 2 this is done in a very crude way in terms of the mass model, where the transfers are expressed in mass units, contrary to the price model, where the transfers are expressed in money units. Figure 6 shows the corresponding material balance, including the material balance equations (the last equation for the "global" material balance area is simply the sum of the equations of the "local" material balance area).

One can use the system of equations to determine, for example the sulphur release to the environment (a_{24}, a_{44}, a_{54}) if there are no constraints for such releases. If one assumes, however, that there are standards which limit the releases a_{24} to a certain value, then one can analyze what the possible consequences of such a limitation could be.

It is clear that the best solution of the sulphur dioxide problem would be desulphurization of oil and coal directly. However, in the case of coal this is not at all possible, and in the case of oil it is very expensive: it has been estimated that the reduction of the emission by 1 t SO_2 would cost about US $ 1000 [17]. Additionally, the question arises of what could be done with the enormous amounts of sulphur available in case of complete desulphurization of raw oil in the refineries: 50 million t sulphur would be obtained annually this way, whereas the world market amounts to only about 30 million t [20].

These questions must be treated in an appropriate input-output price model, this has already been done on a limited scale for regional cases. However, one has to realize that one cannot treat these problems in an isolated way for one pollutant. Here the question of standards for different pollutants comes in (SO_2, NO_x, radioactive gases), and one must consider the problem of a fair balance between these different standards. In any case, one may say that the introduction of similar environmental regulations as they already exist today in the nuclear industry would have major economic implications--we may view the nuclear industry as a forerunner in this field.

Concluding Remarks

We have surveyed existing material balances in nature, and seen that man's growing activities will disturb these material balances on a global scale. Furthermore, we have attempted to show that the magnitude of the problems produces questions which classical discipline-oriented work answer, hence the need for systems approaches. The idea of material accountability has already been proposed by different groups, and what has proven successful in the case of safeguards could serve as a very valuable tool in rather diverse situations in the natural environment and in the economy.

Figure 7, which has been taken from Ref. [24], attempts to represent in the form of a flow sheet the complex interrelations among the main aspects of this paper:

- material balance models
- verification of the models by measurements at strategic points
- economic accountability (input-output analyses).

The preceding chapters have given examples of the individual aspects. In a recycling scheme, the diagram illustrates a problem mentioned several times: the problem of the appropriate balance of models and monitoring systems.

It seems still too early for an international accountability system, for example, for pollutants, although this has been envisaged already by some groups [1], [8]. Even if the data base exists there may be difficulties of access to it and problems to organize, for example, a world-wide reporting system. In this connection it is important to realize that in a specific case such an international accountability system does exist which has proven workable for the plant operators and for the safeguards authority and which can be implemented with a reasonable budget (the 1974 budget amounts to a staff of 100 members and US $ 3 million including R & D).

It has to be stressed that international political considerations urgently called for setting up the IAEA safeguards system. At present the issue of environmental pollution control may not be so urgent; one remembers the difficult problem of establishing a register of radioactive waste discharges. However, the rapidly increasing magnitude of the problem demands that steps nevertheless be taken.

Tab.1: SO_2 Data (Source : Büker e.a)

GENERAL

Natural SO_2 concentration [$\mu g/m^3$]	10
Limit for long term SO_2 concentration:	
VDI [$\mu g/m^3$]	230
US EPA [$\mu g/m^3$]	80
SO_2 residence time in the atmosphere [d]	1 - 6

RUHR AREA

	Emission [10^6 t/a]
Power plants	80 · 0.44
Residential	80 · 0.13
Industry	80 · 0.64
Transportation	80 · 0.01
Sum	80 · 1.22

	Immission (Inventory) [$\mu g/m^3$] 1)	2)
Power plants	80 · 1.79	80 · 13.7
Residential	80 · 0.53	80 · 4.0
Industry	80 · 2.60	80 · 20.0
Transportation	80 · 0.04	80 · 0.3
Sum	80 · 4.96	80 · 38

1) At a wind speed of 4.5 m/sec

2) At the 7th day of a temperature inversion situation

Tab.2: Input-Output - Matrix for Sulphur

(Mass units transferred per reference time)

$$\begin{array}{lcccc}
 & \text{Refinery + Oil Consumer} & \text{Industry} & \text{Sulphur Consumer} & \text{Environment} \\
\text{Oil well + Coal mine} & a_{11} & — & — & — \\
\text{Refineries + Oil Consumer} & — & a_{22} & — & a_{24} \\
\text{Sulphur mines} & — & a_{32} & — & — \\
\text{Industry (without ref.)} & a_{41} & a_{42} & a_{43} & a_{44} \\
\text{Sulphur Consumer} & — & — & — & a_{54}
\end{array}$$

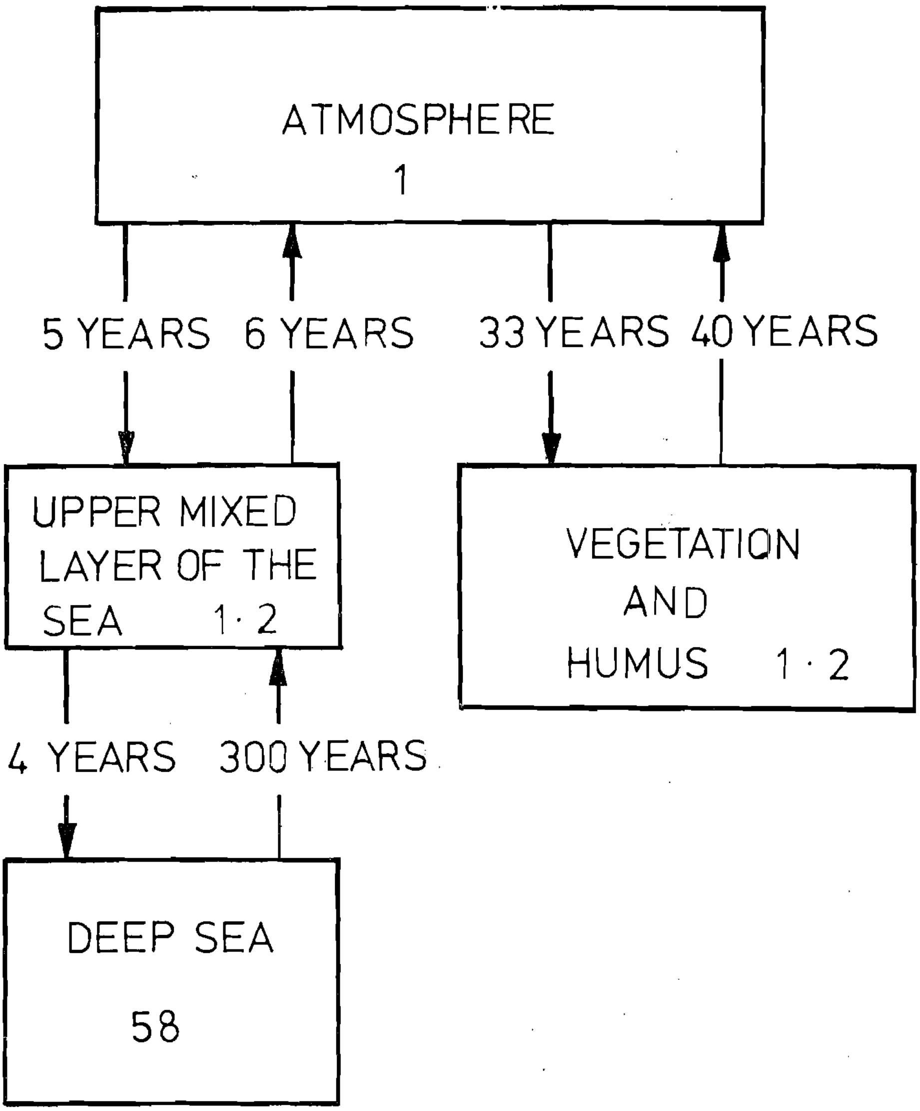
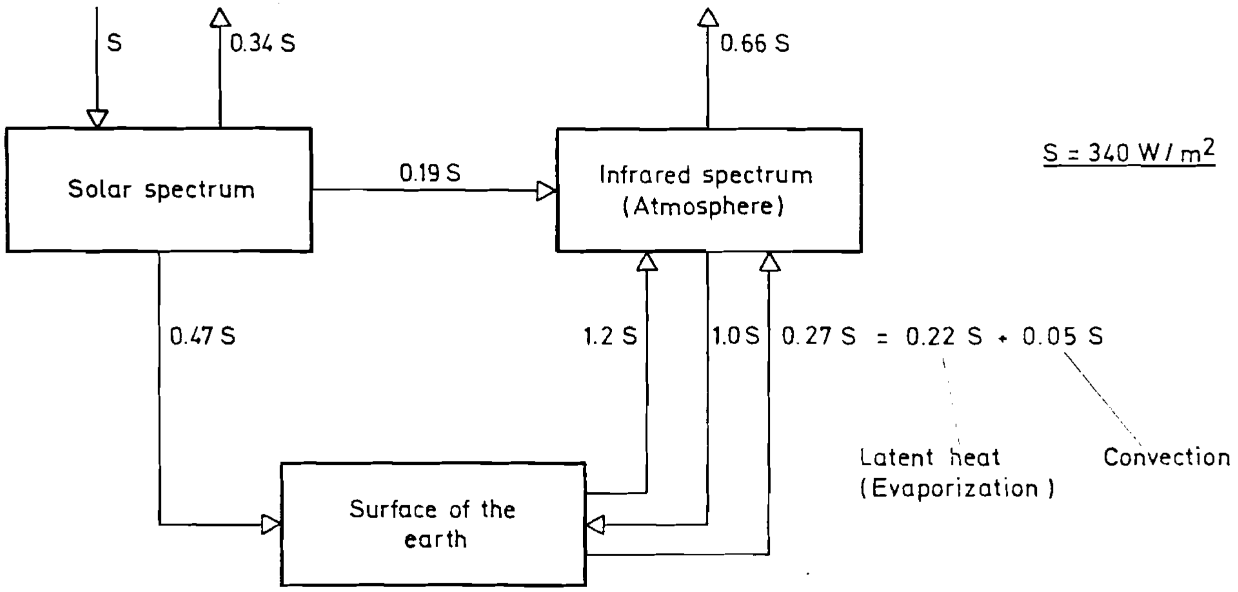
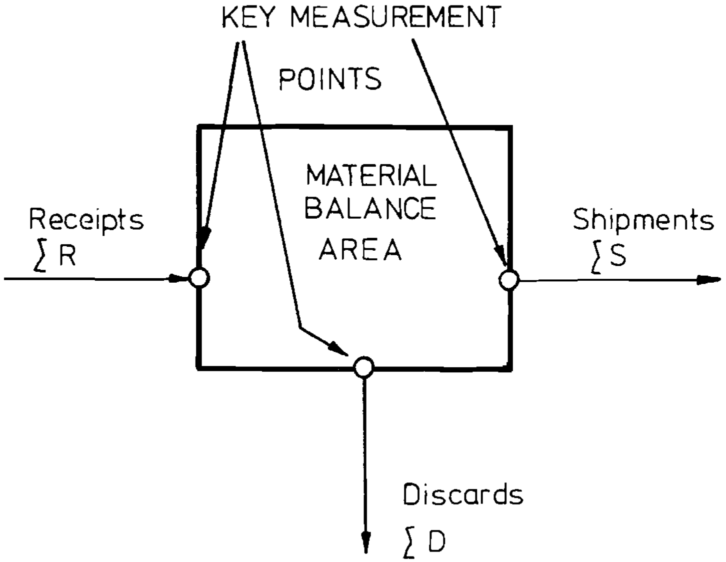


FIG.1: CARBON DIOXIDE CYCLE OF THE EARTH
FIGURES INDICATE CONTENT AS MULTIPLES
OF ATMOSPHERIC CONTENT.
SOURCE : SAWYER

Fig.2 Distribution of Solar Power Input





time t_0 :

Beginning Physical Inventory PI_0

time t_1 :

Book Inventory
$BI = PI_0 + \sum R - \sum S - \sum D$
Ending Physical Inventory PI_1
$MUF = BI - PI_1$

Fig. 3 : The Material Balance Concept

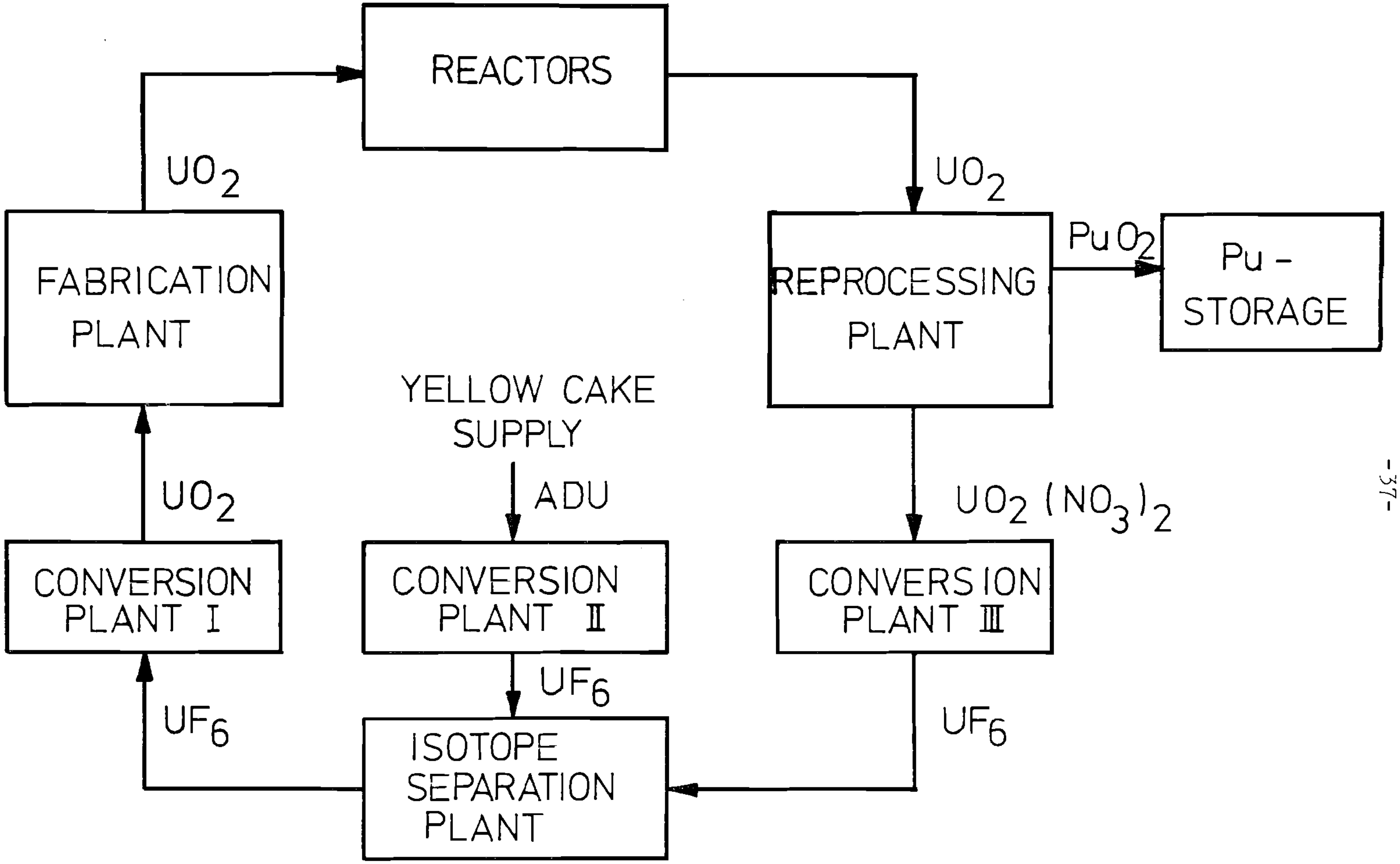


FIG. 4 : REFERENCE FUEL CYCLE WITH NUCLEAR FACILITIES.

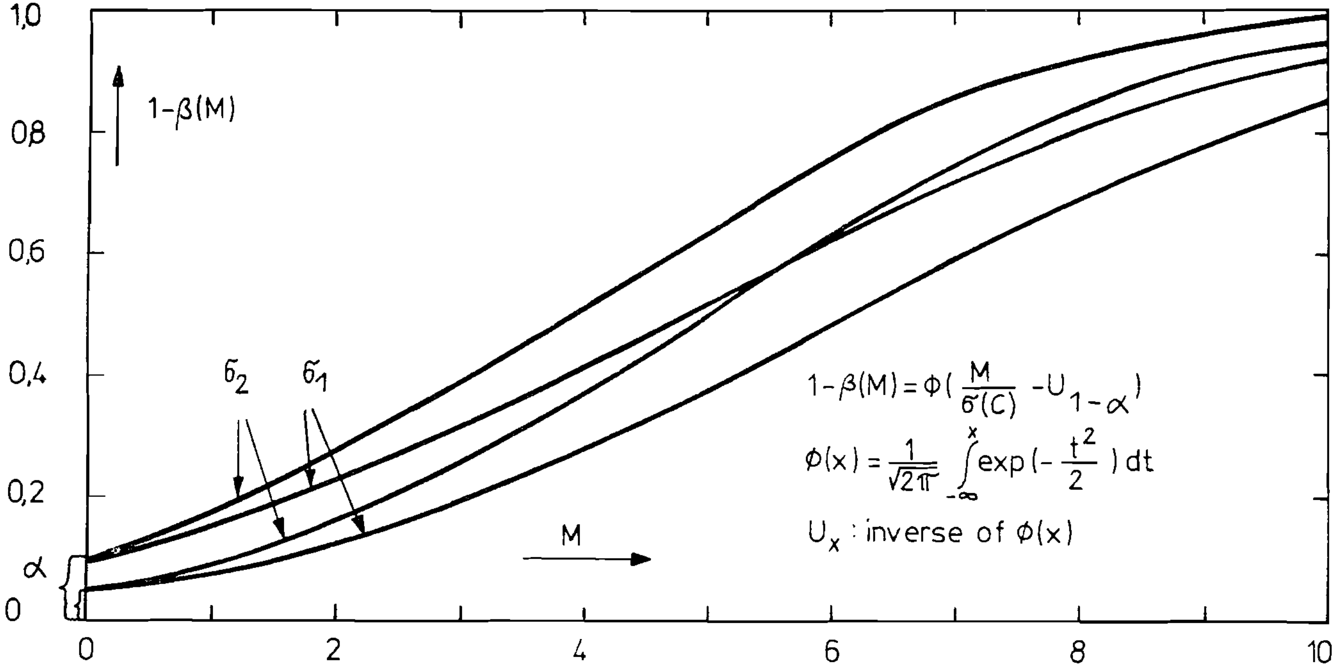


Fig:5: Effectivity of a Safeguards System (power curve)

Typical relation between probability of detection $1-\beta(M)$, amount M assumed to be diverted, false alarm probability α and effort C, for one material balance area and one inventory period ($\sigma_1 = 3.75$, $\sigma_2 = 3.03$)

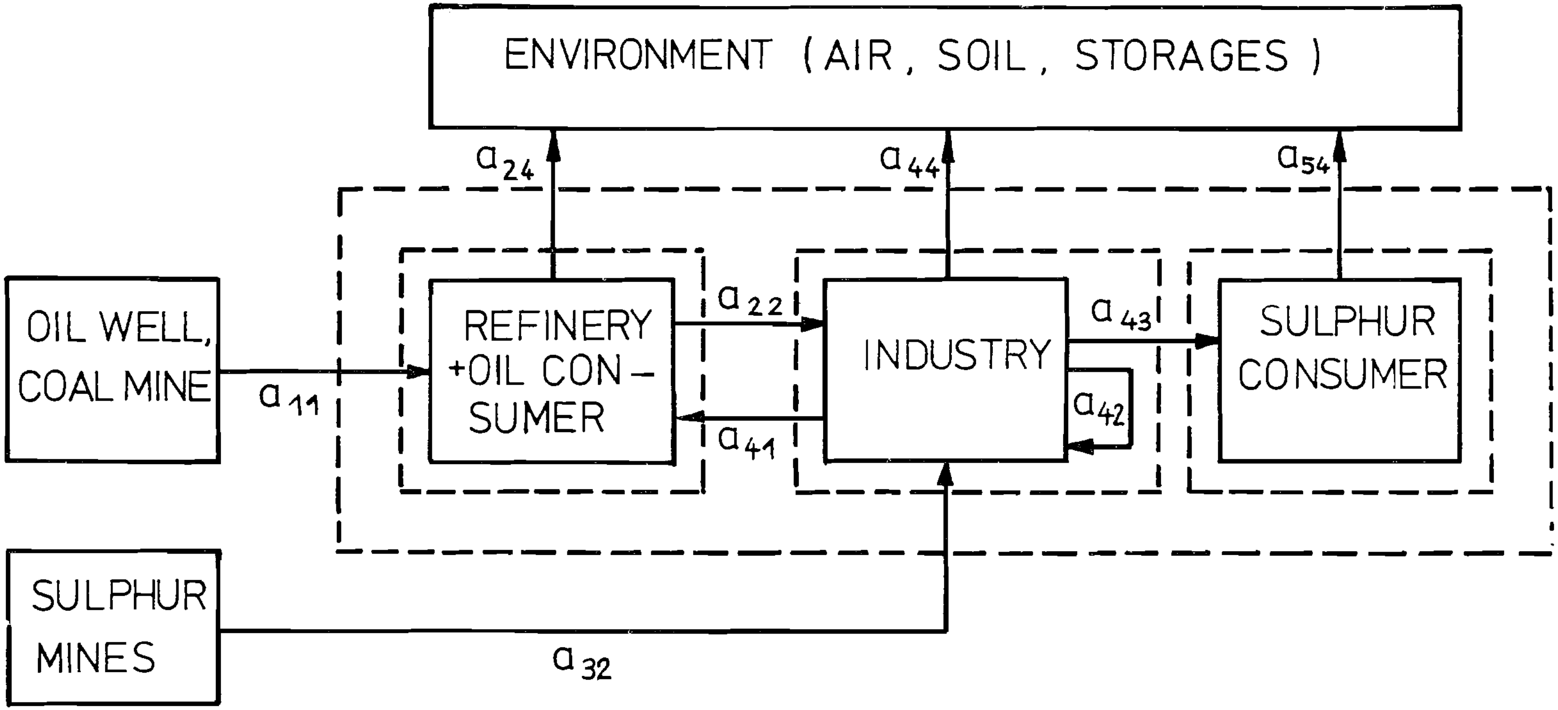
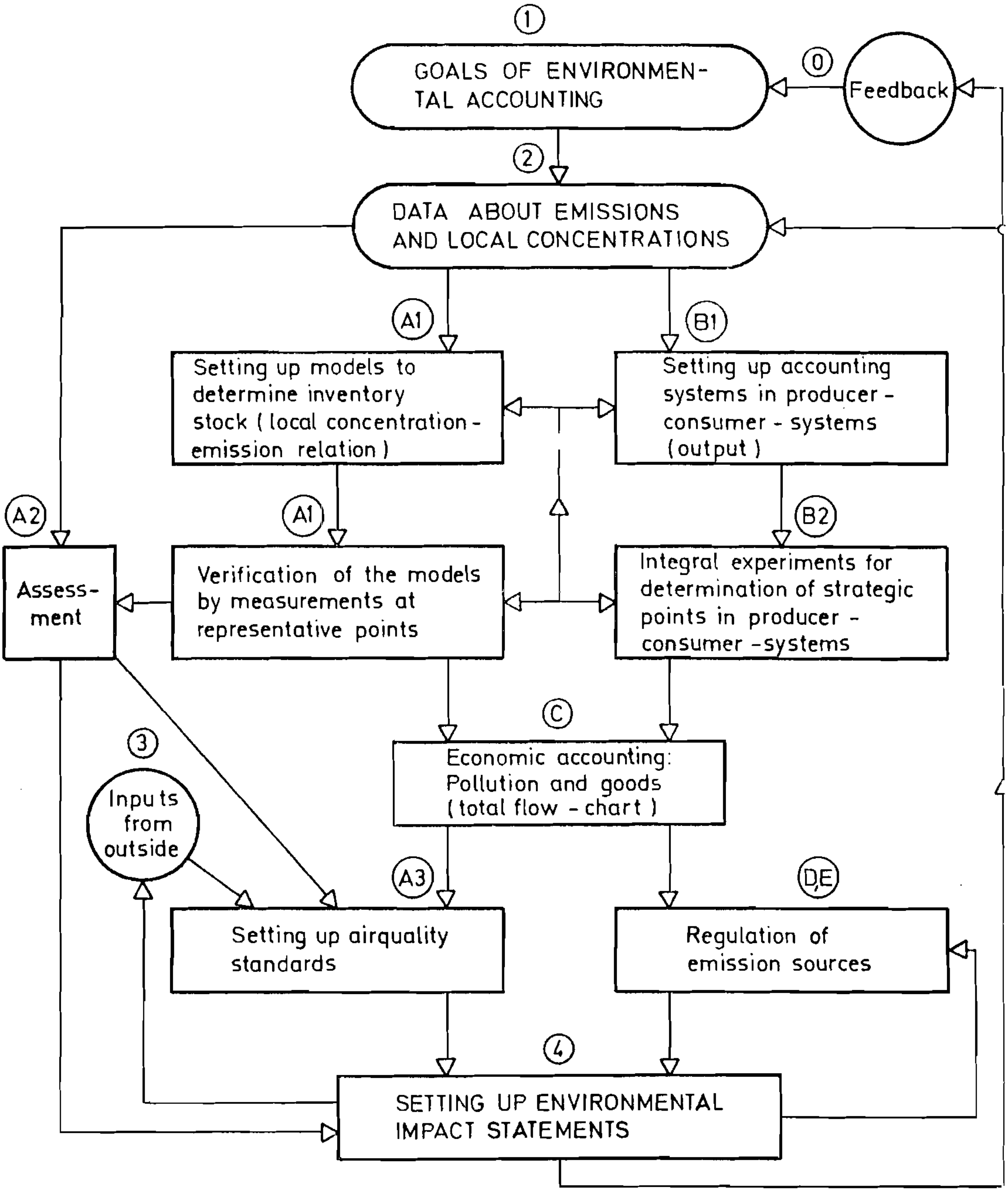


FIG. 6 : MATERIAL ACCOUNTANCY REPRESENTATION OF THE INPUT-OUTPUT APPROACH FOR THE FLOW OF SULPHUR.

MATERIAL BALANCE EQUATIONS (STATIONARY STATE ASSUMED)

$$\begin{aligned} a_{11} + a_{41} - a_{22} - a_{24} &= 0 \\ a_{22} + a_{32} - a_{41} - a_{43} - a_{44} &= 0 \\ a_{43} - a_{54} &= 0 \\ \hline a_{11} + a_{32} - a_{24} - a_{44} - a_{54} &= 0 \end{aligned}$$

Fig. 7 Environmental Accountability



References

[1] Kneese, A.V., Ayres, R.U., and d'Arge, R.C. Economics and the Environment. The John Hopkins Press, 1970.

[2] Häfele, W. "Stoffbilanzen: Beiträge zur Umweltgestaltung A7." Erich Schmidt, Verlag, 1972.

[3] Preuschen, G. "Über die Lebensbedrohung der Menschheit durch die Veränderung des Sauerstoff-Kohlensäure-Verhältnisses der Atmosphäre." Paper presented at the Internationale Lebensschutztagung in Wiesbaden, December 1970.

[4] Man's Impact on the Global Environment. Report of the Study of Critical Environmental Problems (SCEP). Cambridge, Tre MIT Press, 1972.

[5] Sawyer, J.S. "Man-made Carbon Dioxide and the 'Greenhouse' Effect." Nature, Vol. 239, No. 5366 (Sept. 1972), 23-26.

[6] Zimen, K.E., and Altenhein, F.K. "The Future Burden of Industrial CO_2 on the Atmosphere and the Oceans." Die Naturwissenschaften, 60. Jhrgg, Heft 4, (1973) 198-199.

[7] Häfele, W. "Energy Systems." Paper presented at the IIASA Planning Conference on Energy Systems. Laxenburg, Austria, 1973.

[8] Matthews, W.H., Kellegg, W.W., Robinson, G.D. (eds.). Man's Impact on the Climate. Cambridge, The MIT Press, 1971, pp. 447 ff.

[9] Private information from W.W. Kellogg.

[10] Raschke, E., Bandeen, W.R. "The radiation balance of the planet earth from radiation measurements of the satellite Nimbus II." J. of Appl. Meteorology, Vol 9 (1970) 215.

[11] "The Structure and Content of Agreements between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear weapons." IAEA Document, JNF URG/153 (May 1971).

[12] Häfele, W. "Systems Analysis in Safeguards of Nuclear Material." Proceedings of the Fourth International Conference on the Peaceful Uses of Atomic Energy. Geneva, 6- September 1971, Vol. 9, pp. 303-322.

[13] Kraemer, R., and Beyrich, W. (eds). "Joint Integral Safeguards Experiment (JEX 70) at the Eurochemic Reprocessing Plant Mol, Belgium." EUR 4576 1, KFK 1100 (July 1971).

[14] Avenhaus, R., Gupta, D. "Effective Application of Safeguards Manpower and Other Techniques in Nuclear Fuel Cycles." Proceedings of the IAEA Symposium on Safeguards Techniques in Karlsruhe, Vol. I, (1970) pp. 345-371.

[15] Leachman R.B., and Althoff, P. (eds). *Preventing Nuclear Theft: Guidelines for Industry and Government*. New York, Praeger Publishers, 1972, pp. 319-340.

[16] Stewart, K.B. "A Cost-Effectiveness Approach to Inventory Verification." Proceedings of the IAEA Symposium on Safeguards Techniques in Karlsruhe, Vol. II, (1970) pp. 387-409.

[17] Avenhaus, R., Höpfinger, E. "Optimal Sampling for Safeguarding Nuclear Material." *Op. Res. Verfahren*, *XII* (1972), 1-22.

[18] Leontief, W. "Environmental Repercussions and the Economic Structure: An Input-Output Approach." RESTAT, Vol. 52, (1970) 253-271.

[19] Jürgensen, H. "Allokationseffekte der Social Costs im Umweltschutz." Untersuchung zur Anwendung des Verursachungsprinzips-Gutachten erstellt dem Bundesminister des Innern, Hamburg, October 1972.

[20] Märzendorfer, H. "Thermische Kraftwerke im Zeitalter des Umweltschutzes." *OEZE*, Jhg 25, Heft 9, (1972) 348-354.

[21] Büker, H., Jansen, P., Sassin, W., Schikarski, W. (eds). *Kernenergie und Umwelt*. Juel-929-HT-WT KFK 366 (March 1973).

[22] Shande et al. S. "A Stdy of the Potential Radiological Impact of an Expanding Nuclear Power Industry in the Tennessee Valley Region." IAEA/NEA/WHO Symposium on Environmental Behaviour of Radionuclides Released in the Nuclear Industry, May 1973.

[23] Fletcher et al. I.F. "Modeling the Regional Transport of Radionuclides in a Major United State River Basin." IAEA/NEA/WHO Symposium on Environmental Behaviour of Radionuclides Released in the Nuclear Industry, May 1973.

[24] Gupta et al. D. "Umweltbilanzen - ein Kernproblem der Umweltschutz-Politik." Paper presented at the second international working group "Anwendung des Verursacherprinzips im Gewässerschutz", November 20-21, 1972, in Karlsruhe [to be published].