THE "COMPASS" PROJECT:
ATMOSPHERIC PATHWAYS AND IMPACTS.

BY

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SUMMARY

This report is a part of the OECD project "Comparative Assessment
of Environmental Implications of Various Energy Systems"
(COMPASS project) and contains a discussion of residuals
(pollutants) emitted to the atmosphere from fossil fuel energy
production.

The following six priority residuals have been selected: sulphur
oxides, nitrogen oxides, organic compounds, mercury, cadmium, and
carbon dioxide.

The atmospheric residuals are discussed with respect to dispersion
and transformation in the atmosphere, deposition to the ground,
and impact on different receptors. The following seven impact
categories have been selected: human health, visibility, climate,
water quality and aquatic life, soil quality, vegetation, and
materials.

The discussion is pertinent to the present fossil fuel energy
production of the main OECD regions, and no attempt has been
made to quantify the specific pathways and impacts of a given
energy production unit.

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1   INTRODUCTION

The COMPASS project* was started in May 1979, when the Environment
Ministers of the OECD countries suggested that the OECD
Environment Committee examine the environmental implications of
all forms of energy, including the nature and magnitude of the
various impacts associated with the different energy systems.
The main objective of this examination is to provide a basis for
policy makers to take account of the environmental impacts of
energy technologies, when developing strategies for the transition
from primary reliance on oil to a more balanced set of energy
sources (OECD, 1980).

Through 1979 and 1980 the plans of the projects were developed by
the OECD Secretariat, the Group of Energy and Environment, and by
various working groups and consultants.

In December 1980 a workshop, held at the OECD, discussed the
preparation of reports on the following three main areas:

- Energy sources,
- Media pathways and impacts,
- Environmental implications of space heating and cooling.

These areas were to be treated in more detail by consultants,
according to the guidelines from the workshop.

The intention of the report presented here is to discuss the most
important air residuals (air pollutants) which are emitted from

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*"COMPASS" means "Comparative Assessment of Environmental Implications of
 Various Energy Systems".

fossil fuel energy production, their transport and transformation
in the atmosphere, and their impacts on the different receptors.
The discussion is general, and is intended to cover the areas of
most importance to fossil fuel energy production in the main OECD
regions today and in the next decade. No attempt has been made to
quantify the impacts of a given energy production unit, due to the
lack of necessary data on the plant and site characteristics, and
the area of consideration. Among the site-specific factors, neces-
sary for an in-depth impact analysis of a single energy production
unit, are detailed information on

    topography (land, sea, valleys mountains),
    meteorology (wind, temperature, humidity, precipitation,
                  solar radiation),
    vegetation, (natural, cultivated),
    geology,   (soil),
    population distribution.

Even with this information available, a reliable quantitative
impact assessment is difficult, due to the lack of basic under-
standing of many of the phenomena involved. Many of the impacts
of fossil fuel energy production are not localised to the vicinity
of a single production unit, but occur over larger regions due to
the combined influence of many sources of different categories.
Thus, it may be very difficult, if not impossible, to single
out the net impact of each source.

In Section 2, the priority residuals and their impact categories
are selected. In Section 3, the pathways and transmission models
are discussed, and a discussion of the different impacts is
presented in Section 4.

2   SELECTION OF RESIDUALS AND IMPACT CATEGORIES

The selection of residuals has been guided by :
    1. Significance of health or environmental impact;
    2. Amenability of the pathway-impact chain to quantification;
    3. Existence of regulations in OECD countries.

Of these three items, the first is considered the most important.

The residuals given in Table 1 have been selected as priority residuals.

Table 1: List of priority residuals.

Sulphur oxides	(SO_x)
Nitrogen oxides	(NO_x)
Organic compounds	
Mercury	(Hg)
Cadmium	(Cd)
Carbon dioxide	(CO_2)

Organic compounds include volatile organics, such as hydrocarbons, aldehydes etc., as well as polyaromatic organic matter (POM).

These residuals have a variety of sources, and for some of them energy production is not the major source. The residuals have, however, received considerable attention in a number of energy-related environmental evaluations.

Among other residuals, which will not be discussed here, the following can be mentioned:

> Arsenic
> Vanadium
> Nickel
> Lead
> Hydrochloric acid
> Dust
> Nitrous oxide
> Radioactive compounds

In Table 2 the main sources of the priority residuals are
indicated. The sources are divided in two categories. The first
is related to energy production, while the second is not.

Table 2: Sources of the priority residuals.

Residual	Sources related to energy production	Other sources
Sulphur oxides	Combustion of coal and fuel oil	Refining of metals, especially non-ferrous
Nitrogen oxides	Combustion of coal, fuel oil and natural gas	Combustion of gasoline and diesel oil, industrial processes.
Organic compounds	Refining of crude oil; combustion of coal, fuel oil, and biomass.	Combustion of gasoline and diesel oil, industrial processes, solvent use.
Mercury	Combustion of coal	Industrial processes
Cadmium	Combustion of coal	Incinerators, fertilizers, industrial processes.
Carbon dioxide	Combustion of coal, fuel oil and natural gas	All combustion of fossil fuel, and biomass.

The priority residuals can have health and environmental impact
as primary pollutants, i.e., in the form they are emitted into
the atmosphere, or as secondary pollutants, i.e., as reaction
products with other components present in the atmosphere. The most
important energy related secondary pollutants are secondary
aerosol, acid precipitation, and photochemical oxidants.

The impact categories, which will be subject to further discussion
in this report, are:

1. Human health
2. Visibility
3. Climate
4. Water quality and aquatic life
5. Soil quality
6. Vegetation
7. Materials.

3 PATHWAYS AND TRANSMISSION MODELS

The pathways of residuals in the atmosphere can be thought to consist of three stages:

1 Dispersion
2 Transformation
3 Deposition

Dispersion means dilution by the surrounding air and transport with the prevailing winds. Transformation means physical and chemical changes which the residuals are undergoing, and deposition means removal from the atmosphere. Dispersion and transformation occur simultaneously in the atmosphere, but are treated separately in this report.

The dispersion (and impact) of an air pollutant can take place on different scales. The scale may be defined as the horizontal length which is typical of the phenomenon in question. The following scales are commonly used:

Name	Order of magnitude length (km)
Local scale	10
Mesoscale	100
Continental scale	1000
Global scale	10000

For the discussion of the impact of a certain residual, the scale is dependent on the magnitude of emissions, the concentration level associated with adverse effects and the residence time of the residual in the atmosphere. The residence time, which is dependent on the chemical and physical characteristics of the residual, can vary considerably for the different components, from the order of days for sulphur dioxide to the order of years for carbon dioxide.

3.1 Dispersion

3.1.1 General aspects*

The most important meteorological elements in connection with air pollution problems are wind speed and direction. It is convenient to consider the dispersion process as a combination of transport and turbulent diffusion. The plume of pollutants as a whole will be transported by the mean wind flow. The turbulence, which consists of eddies of different sizes, will diffuse the plume and increase its size.

Atmospheric turbulence is divided into two types, depending on whether it is of thermal or mechanical origin. Mechanical turbulence arises from the movement of air over the earth's surface, and is influenced by objects resisting the air motion. The intensity of mechanical turbulence increases with wind speed and with the surface roughness.

Convective or thermal turbulence is caused largely by differences in temperature between the surface and the overlying air. The vertical temperature gradient in the lowest layer of the atmosphere, or the static stability of the atmosphere, is an important indicator of thermal turbulence.

Thermal and mechanical turbulence generally occur simultaneously, and the two types cannot be completely separated.

The structure of the near-surface layer, the planetary boundary layer, experiences a diurnal variation which affects pollutant transport and diffusion. At night, surface long-wave radiation cools the near-surface air and causes the formation of a ground-based stable layer, or inversion. Pollutants emitted into this layer undergo little mixing or dilution, while those emitted above it may be slowly mixed through a large depth of the atmosphere above the ground-based inversion without reaching the surface. In the morning, as solar radiation heats the surface and causes convective mixing, the stable layer is eroded from below

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*In part adapted from Whelpdale (1978).

and pollutants mix through progressively greater depths of the
atmosphere, frequently up to one or two kilometres, depending on
the time of year and meteorological conditions. The following
night, the cycle is repeated: pollutants well-mixed from the
previous day remain above the newly formed surface inversion,
and new pollutants are injected into the lower stable layers.
Although this picture is rather simple and pertains primarily
to fair-weather conditions in mid-latitude, continental areas,
it does indicate the complexity of the atmospheric processes
controlling pollutant behaviour and the difficulty in modelling
these processes.

Frequently, for lack of time and space resolution in meteorologi-
cal and pollutant measurements, one resorts to envisaging the
transport as occurring at the speed of the mean wind in a layer
through which the pollutants are asssumed to be uniformly mixed.

Pollutants can be transported over large distances under a variety
of meteorological conditions. Plumes emitted into a stable atmos-
phere undergo little vertical or horizontal diffusion and can
travel for several hundred kilometres before being dispersed or
incorporated into clouds. On the other hand, when emissions from
diverse sources over a broad area accumulate in stagnating air
associated with anticyclonic conditions, the pollutants become
well mixed by day-time convection, and can be slowly transported
in the southerly flows to the west of the high pressure centres,
to affect areas several hundreds of kilometres across for a
couple of days at a time.

3.1.2 Dispersion_models[*]

The Gaussian plume model is by far the most commonly applied dis-
persion model on the local scale. The theoretical basis of this
model is the assumption that the shape of a diffusing cloud relea-
sed from an instantaneous point source is normal, or Gaussian.
A continuous point source is then treated by the superposition of

[*]Adapted from Eliassen (1981).

many Gaussian "puffs". The models in practical use employ different dispersion parameters depending on the emission height, and the thermal and mechanical turbulence. They further include wind speed variation with height, and treat the plume rise in great detail. The models can be modified to incorporate deposition to the ground and first order chemical removal. With additonal modification they can to some extent include topographical effects, aerodynamic downwash and fumigation effects, (Sivertsen, 1980).

The Gaussian plume models show weaknesses when the wind field or the topography is complex. Also, calm wind situations cannot be handled adequately. Chemical processes other than first order removal cannot be included in the models. Comparison with air quality data often gives unsatisfactory agreement for short averaging times (hours). For longer averaging times (days or longer) the performance is improving.

When the spatial scale increases from local to mesoscale, the results of Gaussian plume models become increasingly uncertain. One may then use box models or grid models. These models are derived from the equation of mass conservation, and the solution of the equation, with the appropriate initial and boundary conditions, gives the time-dependent three-dimensional concentration field. Numerical techniques for the solutions are well developed but may require considerable computer capacity. It should be emphasized that any such solution depends on the quality of the input data, such as the emissions, the three-dimensional wind field and turbulence coefficients. In practice, a sufficiently dense network of meteorological observations is often lacking.

In some cases, the airflow on the mesoscale is determined more by internal forcing within the region than by the external boundary conditions. An example of this is sea breeze which is important from an air pollution point of view. Generally, the mesoscale represents a difficult intermediate scale for air pollution modelling.

On the continental scale, one can usually take advantage of the
fact that the pollutants have had time to mix vertically throughout
the atmospheric boundary layer. The concentration is then independ-
ent of the vertical co-ordinate. The same assumption is usually
made for the horizontal wind. In many cases the models are further
simplified by assuming that the mixing height is constant, and by
ignoring mass transport up to the free atmosphere.

The mass balance equations are either integrated in a Eulerian
grid, or along trajectories in a Lagrangian framework. The Eulerian
and Lagrangian models are based on an hour-to-hour integration of
an advection-diffusion equation, and are in principle capable of
describing events on a time scale of days or less. The Eulerian
approach needs input data from the entire model domain (emissions,
winds, precipitation, cloudiness) and require considerable com-
puter capacity.

The Lagrangian appoach can be either source-oriented or receptor-
oriented. The receptor-oriented models are suited for treatment
of non-linear air chemistry as long as well-mixed parcels of air
with no vertical or lateral diffusion are considered. Lagrangian
models have been applied to case studies, and for the evaluation
of long range transport over months and years (e.g. OECD, 1977;
Eliassen 1978).

Statistical models have been developed (Rodhe, 1972; Bolin and
Persson, 1975; Fisher, 1975) from which long term (annual)
average concentration fields are obtained, withou having to
integrate the advection-diffusion equation over a long time period.

The various types of models dealing with air pollutants on the
global scale are based on the mass conservation equation. Different
models exist with a varying degree of sophistication in the
description of pollutant transport and air chemistry.

The most simple description of transport is found in the so-called
one-dimensional models, which attempt to describe the globally

averaged vertical distribution of pollutants. The simple one-dimensional model formulation permits the inclusion of very sophisticated chemical reaction schemes. Studies with such models have usually concentrated on stratospheric air chemistry, but the troposphere has often been included in the model domain.

Next in meteorological sophistication come the two-dimensional models. These models normally describe the zonally-averaged pollutant concentration in a height-latitude plane. They may be designed to incorporate both the troposphere and the stratosphere, or concentrate on tropospheric conditions (Isaksen and Rodhe, 1978). The treatment of air chemistry is generally less sophisticated than in the one-dimensional models.

Finally, work is going on to utilize the information provided by three-dimensional, general circulation models for the study of global distribution of trace gases. For example, the global distribution of nitrous oxide and carbon dioxide has been simulated with three-dimensional general circulation models (Levy et al., 1979; Manabe and Stouffer, 1980). Only relatively simple chemical source and sink terms were used. A similar calculation, but with components requiring large chemical reaction schemes, would need a vast computer capacity and is not possible at present.

3.2 Transformation

Transformation in the atmosphere means the chemical and physical changes which the residuals undergo, i.e., the formation of secondary pollutants from primary pollutants. The most important secondary pollutants related to energy production are oxidized sulphur, nitrogen and carbon compounds, as well as photochemical oxidants. The oxidized sulphur compounds occur mainly in the aerosol phase as sulphuric acid or ammonium sulphate. The nitrogen and carbon compounds occur both in the gaseous and the aerosol phase. Photochemical oxidants are formed by reactions between nitrogen oxides and organic compounds in the presence of sunlight. There are strong interactions between the various oxidation processes in the atmosphere.

3.2.1 Sulphur oxides.*

The chemistry of sulphur dioxide in the atmosphere is complex.
There are many possible gas-phase reactions (homogeneous
reactions) and reactions involving liquid droplets and solid
particulates (heterogeneous reactions) by which SO_2 may be trans-
formed into sulphate. In turn, several factors, such as temperature,
amount of sunlight, concentrations of other substances (particu-
larly nitrogen oxides, hydrocarbons, water and aerosols), influence
the rates of oxidation. A knowledge of these transformation
processes and rates is very important in order to be able to
predict the concentrations of the various species along the tran-
sport path.

Reaction rates for gas-phase oxidation of SO_2 range from a few
tenths of one per cent to a few per cent per hour. For the western
European summer, Eggleton and Cox (1978) suggest values of 0.5 to
$5\% h^{-1}$ in sunlight, depending on the degree of pollution of the
atmosphere, with the lower figure relating to clean air. The most
important mechanisms are those involving the oxidation of SO_2 by
other short-lived pollutants which have been photochemically
generated (Eggleton and Cox, 1978). Because these reactions are
dependent on solar radiation, their importance decreases signi-
ficantly in wintertime and at night.

Although the liquid-phase oxidation of SO_2 has been extensively
studied under a variety of experimental conditions, there is still
considerable disagreement in the literature concerning the rates
of reaction. Catalyzed oxidation in the presence of metals (e.g.,
iron, manganese) is important in urban plumes and perhaps urban
fogs where their concentrations are sufficiently high, but pro-
bably not in cleaner, rural air. Liquid-phase oxidation involving
the strong oxidizing agents ozone and hydrogen peroxide is also
considered very important (Penkett et al., 1979). The effect of
atmospheric ammonia is to retard the increase in acidity of the
solution resulting in further dissolution and liquid-phase
oxidation of SO_2. It is also important in the final transformation

*Adapted from Whelpdale, (1978).

of sulphuric acid to ammonium sulphate. In summary, the liquid-phase oxidation reactions are generally thought to be of comparable importance to the gas-phase reactions.

There is a variety of measurements which indicate that SO_2 is both adsorbed and oxidized on the surface of solid particles. This mechanism could be significant in stack plumes. No rate data are available, however, and the importance of these reactions to over-all conversion of SO_2 to sulphate aerosol in the atmosphere cannot be assessed.

3.2.2 Nitrogen oxides

Nitrogen oxides are less soluble in water than the sulphur oxides. Hence, the gas phase ractions are considered more important than the reactions in the aerosol phase.

The uncatalyzed reaction between nitric oxide (NO) and oxygen is too slow to have any major importance except in the immediate vicinity of the source. However, nitric oxide is rapidly oxidized to nitrogen dioxide (NO_2) in the presence of ozone or other strong oxidizing agents, such as peroxy radicals. Ozone plays a role in the NO oxidation, both as a natural constituent of the atmosphere and as a reaction product in the photochemical cycle. In the presence of organic compounds and sunlight, the organic and inorganic radicals are being regenerated and can thus be important oxidizing agents even if they occur at very low concentrations. Nitrogen oxides are further oxidized to nitrous acid (HNO_2) and nitric acid (HNO_3). Several reaction paths are possible, and factors like the amount of sunlight and presence of other substances determine the most important paths and the reaction rates.

From a chemical equilibrium point of view, nitric acid is the most stable of the oxidized nitrogen compounds, but in most air pollution situations equilibrium is not attained (Grennfelt, 1980). Due to the relatively high vapour pressure, the nitric acid formed will to some extent remain in the gaseous phase.

Peroxyacyl nitrates and peroxynitric acid are formed in the photochemical reaction cycle. Both are unstable, and the decomposition rates increase with increasing temperature.

3.2.3 Organic compounds

Relatively little is known about transformation in the atmosphere of organic compounds other than those normally associated with the formation of photochemical oxidants. It has been proposed that polyaromatic organic compounds (POM) react with ozone and other oxidizing agents to form new compounds, which in addition may contain sulphur or nitrogen. Direct nitration of POM has also been suggested (Pitts, 1979). Much more research is needed, however, both for identification of the individual compounds and for assessing their impacts.

3.2.4 Photochemical oxidants

The formation of photochemical oxidants has been subject to a multitude of studies in North America since the 1940's and in Europe since the 1960's. Photochemical oxidants can be defined as compounds with a stronger oxidizing potential than oxygen, formed by chain reactions between nitrogen oxides, organic compounds and oxygen in the presence of sunlight. Ozone is the compound formed in the largest quantities and is hence used as an indicator of the oxidant formation, even if ozone also is formed by natural processes. Other oxidants are hydrogen peroxide, peroxyacetyl nitrate (PAN), peroxybenzoyl nitrate (PBzN) and other peroxyacyl nitrates. Nitrogen dioxide and aldehydes are formed as intermediate products.

The chemistry of the oxydant generation is very complex with several hundred possible gas phase reactions. The main formation mechanism, however, can be described by less than 50 individual reactions. The different organic compounds have different ability to participate in the formation process. However, given enough time for the reactions, most organics can take part in the process.

As mentioned in Subsections 3.2.1 and 3.2.2, the oxidation of sulphur and nitrogen oxides is in many cases strongly interrelated,

and particulate sulphate can thus be considered a reaction product
in the photochemical cycle.

The formation of photochemical oxidants can take place on different
scales. Local formation can occur downwind of urban and industrial
areas. Mesoscale formation can occur over larger urban and adjacent
rural areas, for example in coastal regions when land/sea breeze
prevails for several days. Continental scale formation takes
place when a high pressure area is located over a large, highly
industrialized and populated area, for example central Europe or
eastern North America (Guicherit and van Dop, 1977; Wolff et al.,
1977; OECD, 1978; Schjoldager et al., 1981).

Trend studies by OECD, based on 1972-1985 data and projections,
indicate that while sulphur dioxide emissions are being reduced
in many countries, emissions of hydrocarbons and nitrogen oxides
were increasing at an annual reate of about 5% in Europe in the
late 1970's. Control technology cannot significantly impact on
this trend before 1985. Consequently, concern has been expressed
over the likelihood of significantly higher oxidant levels and
more widespread effects during photochemical episodes (NILU, 1978).

3.2.5 Mercury

The main source of mercury related to energy production is
combustion of coal. Mercury is emitted mainly in gaseous form
(90-100%), and the rest is found in the fine particulate phase.
The gas-phase mercury is mostly in elementary form, and the rest
is either inorganic or organic. Relatively little is known about
the chemical transformation of mercury in the atmosphere. It is
well-known, however, that once deposited on the ground, some of
mercury can be reemitted to the atmosphere. Biological activity in
soil and water can change the chemical composition so that
mercury compounds other than those deposited can be reemitted.
It has further been suggested that the reemission from water sur-
faces is reduced when the pH of the water is reduced (Brosset and
Svedung, 1977). Thus, lakes which have been acidified can act
as sinks for atmospheric mercury.

3.2.6 Transformation models

Models have been developed for the transformation of sulphur and nitrogen oxides and for the generation of photochemical oxidants. These models consist of source and sink terms for each of the chemical compounds of interest. The simplest models for SO_2 oxidation incorporate one or two compounds, while the most complicated photochemical models can have the order of a hundred (Demerjian et al., 1974). Each compound can take part in many chemical reaction steps, and the number of steps can thus amount to several hundred. Mathematically, the model is described as a set of first order, non-linear differential equations with time-dependent coefficients. Several numerical solution techniques have been developed (e.g., Hesstvedt et al., 1978).

The transformation models can be incorporated into dispersion models of various complexity. If large photochemical models are to be included in Eulerian grid models, the computer capacity may be a limiting factor. On the local scale and the mesoscale, photochemical box and grid models have been developed, and their feasibility has been demonstrated (e.g., Liu and Burton, 1979; Derwent and Hov, 1980).

On the continental scale, most of the transformation models so far have been restricted to simple first-order expressions for SO_2 oxidation (OECD, 1977). The inclusion of photochemical models in continental scale dispersion models is underway, however, both in Europe and in North America.

3.3 Deposition

3.3.1 General aspects*

Pollutants are removed from the atmosphere by a number of deposition processes: during dry periods by sedimentation, surface adsorption, and impaction; and during precipitation by in-cloud and below-cloud scavenging. The relative importance of these processes depends both on the climate of a region and on the physical and chemical properties of the specific compounds present. The important deposition processes are known, relatively well

*Adapted from Whelpdale, (1978).

understood, and have been measured in the laboratory and under
certain field conditions; however, modelling them realistically
still poses considerable difficulty.

The deposition of sulphur compounds has been studied more than
the deposition of most other air residuals. Direct surface uptake
of sulphur dioxide is the most important dry removal process.
Turbulent motions bring the gas into contact with the earth's
surface where it is adsorbed, dissolved or undergoes chemical
reaction. The uptake may be limited either by the efficiency of
the gas-phase transfer to the surface, or by the resistance im-
posed by the underlying surface. The oceans, other non-acidic
moist surfaces, and some crops and forest species at certain growth
stages are good sinks, whereas dry, snow-covered surfaces and acid
soils, for example, are less efficient.

Dry deposition of sulphate particles is much less important than
that of SO_2. Sulphate particles are predominantly in the sub-
micrometre size range, and their removal by gravitational sedi-
mentation is slow. Scavenging by forests is thought to be an
effective deposition mechanism, but little quantitataive information
is yet available.

Deposition by precipitation is the result of both in-cloud and
below-cloud capture of SO_2 and particulate sulphate. In-cloud
processes (rain-out) include sulphate particles serving as conden-
sation nuclei, coagulation, and diffusional uptake of SO_2.
Below-cloud processes (wash-out) include interception of particles
by falling drops and diffusional uptake of SO_2.

3.3.2 Deposition models

Dry deposition is normally estimated by assuming that the flux
to the surface is proportional to the ambient concentration at
some distance above the surface. The proportionality coefficient
is called deposition velocity and is dependent on the characte-
ristics of the surface and the pollutant. Deposition velocities
have been experimentally determined for a limited number of com-

ponents, and values, or ranges of values, exist for sulphur
dioxide, nitric oxide, nitrogen dioxide, ozone and PAN.

The wet deposition is expressed as the product of precipitation
amount and pollutant concentration in the precipitation.
The modelling of wet deposition requires knowledge of precipi-
tation amount and frequency, as well as the scavenging efficiency.
In general, the theoretical basis and data availability are less
developed for wet than for dry deposition. For areas with high
sulphur emission density (e.g., parts of central Europe and
eastern North America) dry deposition is larger than wet depo-
sition. For areas farther away from the major source areas, (e.g.,
southern Scandinavia) the wet deposition is larger than the dry
deposition.

Deposition models have relatively low precision for short averaging
times. Over large areas and long averaging times, however, the
model predictions are in reasonable correspondence with the
measured depositions (OECD, 1977).

4   DISCUSSION OF IMPACTS

This chapter contains a discussion of various potential impacts
caused by the selected residuals. In practice it is often difficult
to single out one residual, or pollutant, as the only one in a
complex mixture of atmospheric constituents causing the impact.
Nevertheless, this is the method most often used, and thus a
considerable amount of information is available, both in the form
of separate investigations and review articles. The purpose of this
report is not to make a new comprehensive assessment of the avail-
able references, nor to give a complete bibliography. Instead, the
conclusions from a few review documents are presented, which are
believed to reflect the state-of-the-art in the field. The dis-
cussion is therefore brief, and only the main conclusions from
the various reference sources are presented.

4.1 Human health

4.4.1 Sulphur oxides

Most reviews discuss sulphur oxides and suspended particulate
matter together. This is because both pollutants often originate
from the same source, i.e., combustion of fossil fuels, and
SO_x exists as gaseous SO_2 or particulate SO_4.

The World Health Organization published in 1979 the recommendations
of a Task Group on Environmental Health Criteria for Sulfur Oxides
and Suspended Particulate Matter (WHO, 1979). After having examined
the evidence available, the Task Group proposed threshold levels
"above which some effects on health might be expected among
specified populations for short-term and long-term exposures,
respectively".

The levels proposed by the Task Group are given in Tables 3 and 4.

Table 3: Expected effects of air pollutants on health in selected
segments of the population: effects of short-term
exposures (WHO, 1979).

Expected effects	24-h mean concentration $\mu g/m^3$	
	Sulfur dioxide	Smoke
Excess mortality among the elderly or the chronically sick	500	500
Worsening of the condition of patients with existing respiratory disease	250	250

Table 4: Expected effects of air pollutants on health in selected
segments of the population: effects of long-term
exposures (WHO, 1979).

Expected effects	Annual mean concentration $\mu g/m^3$	
	Sulfur dioxide	Smoke
Increased respiratory symptoms among samples of the general population (adults and children) and increased frequencies of respiratory illnesses among children	100	100

The Tables 3 and 4 use "smoke" instead of suspended particulate
matter. The determination of smoke requires specific procedures
for the sampling and analysis which are given in the WHO-
document.

Based on these threshold levels, the WHO Task Group recommended
guidelines for the protection of public health, given in Table 5.
The Task Group emphasized that the guidelines require careful
interpretation, and the concentrations should not be considered
absolute limites.

Table 5: Guidelines for exposure limits consistent with the
protection of public health (WHO, 1979).

	Concentration ($\mu g/m^3$)	
	Sulfur dioxide	Smoke
24-h mean	100-150	100-150
Annual arithmetic mean	40-60	40-60

As for Tables 3 and 4, the concentrations of Table 5 refer to
specific methods of sampling and analysis (WHO, 1979).

The uncertainties associated with the use of guidelines were further
elaborated by the Task Group (WHO, 1979):

> These guidelines are based on observations among populations
> in the community exposed to a mixture of sulfur dioxide and
> smoke or total suspended particulates and they may not apply
> to situations where only one of the components is present.
> On grounds of prudence, however, it is recommended that the
> levels of each pollutant should be below the values stated.
> It should be stressed again, however, that the data on which
> the guidelines are based are uncertain and each of the guide-
> lines is tentative and subject to review when further inform-
> ation becomes available.

The discussion on health effects of particulate sulphate has been
extensive throughout the 1970's. Statistical relationships between
ambient sulphate concentrations and mortality and morbidity rates
have been developed and used for economic quantification of air
pollution impacts (Lave and Seskin, 1977; OECD, 1981). The medical
basis for the health impact of particulate sulphate was examined
by the WHO Task Group, who concluded "that there is not yet suffi-
cient information available on the effects of community exposures
to sulfuric acid aerosols or suspended sulfates to develop guide-
lines for these air pollutants".

4.1.2 Nitrogen oxides

From the health effects point of view, nitrogen dioxide (NO_2) is the most important of the nitrogen oxides. Furthermore, nitrogen oxides are precursors of ozone and other photochemical oxidants. The World Health Organisation published in 1977 the recommendations of a Task Group on Environmental Health Criteria of Oxides of Nitrogen (WHO, 1977). The lowest observed level for short-term exposure of NO_2 causing adverse effects on the respiratory system of animals and man, was found to be 940 $\mu g/m^3$ (0.5 ppm).

In a report from 1976 the U.S. National Academy of Sciences has indicated a much higher minimum effect-level, 2800 $\mu g/m^3$, for exposures of 15-60 minutes (NAS, 1976).

The WHO Task Group also discussed the use of safety factors in establishing guidelines for ambient air quality, as well as the basis for evaluations of long term exposure. The Task Group concluded in the following way (WHO, 1977):

> Any safety factor must be arbitrary but, obviously, it should be sufficient to protect populations living in large urban communities. Taking into consideration all available inform-ation, the Task Group decided to propose a minimum safety factor of 3-5 for short-term exposure to nitrogen dioxide, and agreed that an exposure limit consistent with the protection of public health might be provided by a nitrogen dioxide concentration of 190 to 320 $\mu g/m^3$ (0.10-0.17 ppm) for a maximum 1-h exposure. This 1-h exposure should not be exceeded more than once per month.
>
> Evidence on the interaction of nitrogen dioxide with other co-existing biologically active air pollutants may well suggest the need for larger safety factors and therefore lower maximum permissible exposure levels. Even now, there may be a need to increase the safety factor in order to protect the highly sensitive portion of the population.
>
> In its evalutation of health risks, the Task Group believed that the biomedical effects of long-term exposure to nitrogen dioxide in man had not been ascertained to the extent that a recommendation for the protection of public health could be made, and therefore did not propose an exposure limit pertaining to long-term averaging times.

4.1.3 Organic compounds

The discussion of organic compounds as primary pollutants will be limited to the listing of certain known carcinogenic compounds. In addition, organic compounds can act as precursors of ozone and other photochemical oxidants.

Polyaromatic organic matter (POM) consist of a large number of compounds formed during combustion of fossil fuels, and some of them have been found to be carcinogenic. In Table 6 a list of carcinogenic POM-compounds is given (Sawicki, 1977). Benzene is another carcinogenic component (EPA, 1978a).

Table 6: Carcinogenic POM-compounds (Sawicki, 1977).

Benzo[a]pyrene
Benzo[a]anthracene
Benzo[e]pyrene
Benzo[a]fluoranthene
Benzo[j]fluoranthene
Benzo[a]phenanthrene (chrysene)
Dibenz[a,h]anthracene
Dibenzo[a,i]pyrene
Dibenzo[h,rst]pentaphene
Dibenzo[a,e]pyrene
Dibenzo[a,h]pyrene
Indeno[1,2,3,cd]pyrene
Benzo[c]acridine
Dibenzo[a,h]acridine
Dibenzo[a,j]acridine

4.1.4 Photochemical oxidants

Recent assessments have been performed by a WHO Task Group (1978), U.S. National Academy of Sciences (NAS, 1977), and U.S. Environmental Protection Agency (EPA, 1978).
As regards exposures to oxidants and ozone at which the effects in man begin to appear, the WHO Task Group concluded in the following way (WHO, 1978):

a) There is presumptive evidence from one controlled exposure study that some effects on the lung function of healthy human subjects might occur with exposure to an ozone level of 200 µg/m³ (0.1 ppm) for 2 h.

b) There is also evidence from general population studies that suggests than 1-h ambient oxidant levels in the range of about 200-500 µg/m³ (0.1-0.25 ppm) may affect lung function in children, increase the frequency of asthma attacks, cause more frequent eye irritation, and reduce athletic performance.

c) There is limited evidence from controlled exposure studies that living in an environment with 1-h oxidant levels within the range of 400-1400 µg/m³ (0.2-0.7 ppm) may exert additional stress on patients with chronic pulmonary disease.

d) There is convincing evidence from controlled human exposure studies that airway resistance may be increased in healthy human subjects following exposure to ozone levels of 700-800 µg/m³ (0.35-0.40 ppm) for 2 h.

Based on this evidence, together with animal studies and some concern of photochemical oxidants as possible carcinogens, the Task Group proposed the following guidelines (WHO, 1978):

1-h levels of ozone of 100-200 µg/m³ (0.05-0.1 ppm)(measured by the chemiluminescence method) could be used as a guideline for the protection of public health. The relatively high natural concentrations of ozone precluded the use of any safety factor.

A 1-h maximum level of 120 µg/m³ (0.06 ppm), which is approximately the highest natural background concentration of oxidants, would be the best single value estimate of the exposure limit for oxidants in the ambient air. This level is in agreement with the long-term goal for photochemical oxidants (as measured by the NBKI method) proposed by a WHO Expert Committee (World Health Organization, 1972).

The issue was raised as to whether the proposed guideline was realistic in view of natural exposure levels and the long-distance transport of ozone. In response to this question, the Group expressed the view that every effort should, nevertheless, be made to develop control strategies for achieving the proposed guideline or at least, for not exceeding it more than once a month.

The NAS and EPA assessments do not seem to be in contrast with the WHO Task Group conclusions, as regards evidence of effects on man. However, in 1979 the EPA set the 1-h ambient air quality standard for ozone to 240 $\mu g/m^3$, which was considered sufficient for the protection of human health (Federal Register, 1979). It is felt that the discrepancy between the EPA and WHO threshold values, in part reflects the legally binding nature of the U.S. Standard and the advisory status of the WHO long-term guideline.

4.2 Visibility*

The visibility of the atmosphere can be reduced by light-absorbing gases, and by aerosols which can both absorb and scatter the light. Nitrogen dioxide is the most important light-absorbing gas, while secondary aerosols in the sub-micrometre size range are more important than the primary aerosol in this respect.

From the 1950's to the 1970's the visibility in some urban areas in northeastern U.S. decreased only slightly, while the visibility in some non-urban areas decreased between 10% and 40% to the point where non-urban visibility was not substantially better than urban visibility. The most significant decline occurred during summer periods.

Secondary aerosol, formed by the oxidation of sulphur oxides, are believed to be the major cause of this reduced visibility, and good correlations have been obtained with the sulphate content of the aerosol.

4.3 Climate

The increasing emission of carbon dioxide and its impact on temperature at the earth's surface is receiving by far the most attention among the various factors which may influence the world's climate in the future. The topic has been subject both to international conferences and comprehensive reviews in the literature. The following assessment is taken mainly from an International Workshop on Energy/Climate Interactions in March 1980,

*Adapted from Wolff (1979).

as reported by Bach and Laurmann (1980), and from the report by Bjørkstrøm et al. (1978) to the Swedish Energy Commission.

It seems to be generally accepted that with the present trend in the fossil fuel combustion, the CO_2 concentration in the atmosphere may double at some time in the next century. The concentration may even increase more than that, and stay much higher than the pre-industrial levels for many centuries. The impact on the climate from these increased CO_2 levels is, however, more uncertain. There seems to be agreement that the temperature at the surface will increase, but the magnitude of the increase is disputed. The predictive models used are of great complexity, but even the most sophisticated models are gross simplifications of the real world. Of crucial importance is the correct modelling of the temperature interactions with the atmospheric humidity.

The calculations by Manabe and coworkers (e.g., Manabe and Wetherald, 1975; Manabe and Stouffer, 1980) indicate that a doubling of the CO_2 level will cause an average temperature increase of 1-3°C. Idso (1980) indicates a much lower temperature increase, but the calculations by Manabe and coworkers are considered as being among the more realistic.

A future temperature increase will be unevenly distributed between the high and low latitudes, with the lowest increase at low latitudes, and highest increase (up to 10°C) in the polar regions. The consequences for the local climate in various regions of the earth are very difficult to predict. It is anticipated that the precipitation patterns may change, with increased precipitation in some and reduced precipitation in other areas.

The impact of temperature increase on the ice cover in arctic areas has also been discussed. The volume of the land ice in Greenland and Antarctic is not likely to change significantly over the next centuries. Some of the Arctic Ocean ice may, however, melt and thus decrease the surface albedo of the north polar regions.

In conclusion, it must be noted that even if the model predictions of changes in the CO_2 level and its impact are very uncertain, they point to potentially significant long-term climatic changes, and much scientific effort should be, and is being, devoted to this important research field.

4.4 Water quality and aquatic life

4.4.1 Acid deposition[*]

Acidification of lakes and rivers during the last decades is a problem of regional scale in Scandinavia and in eastern North America. The acidified areas are underlain by mainly siliceous (quartz-rich) bedrock with sparse or thin soil cover. These same areas now receive decidedly acidic precipitation (weighted average below pH 4.6), and the time trends in acidification of precipitation and inland waters are parallel.

Recent acidification of freshwaters is normally not found in geologically similar, sensitive areas which lie outside the regions of acid precipitation. This regional coincidence both in space and time strongly suggests that aquatic ecosystems are being acidified by atmospheric deposits. The extent of acidification is well known from existing (but few) observations both in Scandinavia and North America of water pH and other chemical characteristics over the years, and indirectly through mapping of lakes and rivers where fish populations have been reduced or lost in recent years. No other cause than acidification with associated altered chemical conditions can explain the present regional fish loss. Surveys of land-use changes associated with agriculture and forestry practices in acidified parts of Norway show no systematic relations with acidified lakes and fish population loss.

Important chemical changes take place when precipitation or snow melt-water is in contact with vegetation and soil, before the water reaches rivers and lakes. One important effect of acid

[*]Adapted from U.N. Economic Commission for Europe (1980).

precipitation on soil is highly increased concentrations of aluminium in the run-off. This has major consequences for aquatic life, and aluminium is now held to be critical element for fish mortality.

Sulphate plays a decisive role in the acidification of fresh water, as a mobile carrier of the hydrogen ions whether the hydrogen ions stem from atmospheric deposits or are produced in the catchment. The input and output of sulphate to catchments are in many cases close to a balance over periods of several years. There is, however, often a retention during dry summers, and a release with autumn rains. This process may produce episodes of very acid stream water, as the sulphate is washed out with equivalent amounts of cations, which in the acidified regions will tend to be hydrogen ions.

The recent acidification of fresh water in parts of Europe and eastern North America has had profound impacts on aquatic life. It can be stated with reliability that all trophic levels are affected. The most immediate concern to the people living in the acidified regions is the major decline in fish populations, but also primary producers, decomposers and invertebrate animals are affected.

High egg and fry mortality in acid water, leading to reduced or lacking younger age classes, is regarded as a main reason for fish decline, but other population responses such as post-spawning extinction are also known. Episodes of massive fish kill of adult fish during acid episodes, especially during snowmelt, are well documented. The fish kills are mainly caused by toxic combinations of water acidity and high aluminium content.

4.4.2 Deposition of mercury

In a number of lakes of southern Sweden it has been found that the mercury content of some fish species has exceeded the threshold limit of 1 ppm for food. No source of mercury other than atmospheric deposition has generally been held responsible for this increased uptake of mercury. It has been shown that the reemission

of mercury from water surfaces is highly pH-dependent. Increased acidification reduces the reemission, and the Hg ontent of the lakes can thus increase. It has been predicted that continued acidification will increase the number of lakes with high Hg conent in the fish even without a general increase of the atmospheric concentrations of mercury. Many aspects of the transport, deposition and uptake of mercury are, however, poorly understood and much more research is needed in this field (Swedish Energy Commission, 1978).

4.5 Soil quality

4.5.1 Acid deposition*

Several processes are known to acidify soil:

- Root uptake of cations during plant growth.
- Carbonic acid formation from CO_2 derived from respiration of soil, fauna and flora.
- Oxidation of nitrogen and sulphur compounds to nitric acid and sulphuric acid.
- Organic acids produced during decomposition of plant matter.
- Atmospheric input of acidifying substances, notably sulphuric acid.

Acidification of soil is a slow process in nature, and field detection of effects of additional input of acidifying components is likely to be difficult and slow. Good indicators of soil degradation related to loss of plant productivity are needed. There is agreement that sandy, well-drained soils of intermediate pH are particularly susceptible to pH changes. There are, however, very few indications from field studies of soil acidification due to atmospheric deposition.

Loss of nutrient minerals, which is a natural process caused by weathering, appears to be widespread and enhanced from soils in areas with high deposits of acidifying components.

*Adapted from U.N. Economic Commission for Europe (1980).

When the leaching of plant nutrients from soils exposed to acid deposition occurs faster than the weathering of minerals (which provides new dissolved compounds while consuming H^+ ions), the net loss may be important for plant productivity. Loss of magnesium due to soil acidification is already believed to restrict forest growth in parts of central Europe. Concentrations of aluminium in the soil solution are so high in some acid-impacted soils that possible Al-toxicity affecting tree growth is seriously considered.

In soils with nitrogen and sulphur deficiency, acid precipitation could have a positive growth effect. Douglas fir stands in the Pacific north-west region of the United States are only one example. At the same time, it is suspected that acid precipitation may have caused potassium depletion in some soils in the Pacific north-west. Effects of acid precipitation on forest growth are therefore considered as a nutrition problem (apart from possible direct effects). The increased deposition of nitrogen and sulphur can be regarded as a fertilization, and the increased leaching of nutrient cations caused by increased atmospheric deposition of sulphur compounds will tend towards nutrient deficiencies. Plant requirements for different nutrients and soil properties will determine whether the growth effects will be negative or positive.

Field investigations on possible growth effects in boreal coniferous forests receiving acid precipitation have been inconclusive. However a number of possible effects of acid precipitation on the biological and biochemical processes in forest soil have been identified.

4.2.5 Deposition of cadmium

Concern has been expressed on potential increase of cadmium content in soil and its accumulation in commercial crops. This has been attributed to supply from manure, sludge, fertilizers and industrial sources, and atmospheric deposition from waste and coal combustion. The Swedish Energy Commission (1978) considered the energy-related supply to be of minor importance. However, due to the high toxicity of this residual, attention should be given to all the potential sources.

4.6 Vegetation

4.6.1 Sulphur dioxide*

Sulphur is a major plant nutrient, and low doses of SO_2 may there-
fore have beneficial effects under conditions where the soil is
deficient in sulphur. However, an increased uptake of SO_2 by vege-
tation will cause increasingly severe damage.

Sulphur dioxide enters plant leaves through the stomata openings,
and the major part is dissolved and transported with the water in
the leaf cells. Low doses may stimulate carbon dioxide assimi-
lation, but at higher concentrations photosynthesis is reduced.
Sulphur compounds have also been shown to change a number of
important cellula processes.

Rapid absorbtion in the physiologically most active leaf cells of
toxic concentrations of SO_2 may lead to visible injury. Heavy
injury may kill whole plants. Acute injury of sensitive plants
(e.g., barley, beans, white pine) has been reported mostly at
concentrations of 500 µg SO_2/m^3 for exposure times of a few hours.
However, growth reduction without visible injury occurs at much
lower concentrations.

The dose-response relationship is fairly well known only for a
few forest tree species, such as Scots pine. The data suggest
that detectable growth decreases first occur at average concen-
trations of about 50 µg SO_2/m^3, and that the species is eventually
eliminated when long-term mean concentrations exceed about
200 µg SO_2/m^3. Experience suggests that Norway spruce and silver
fir are more sensitive to SO_2 than Scots pine, whereas Sitka
spruce has greater tolerance. In many cases synergistic effects
(greater than additive effects) of SO_2 and other air pollutants
such as ozone, NO_2 and heavy metals, have been observed.

*Adapted from U.N. Economic Commission for Europe (1980).

International Union of Forest Research Organizations (IUFRO, 1979)
has proposed the following maximal SO_2 concentrations necessary to
maintain full production in higher mountain regions and in boreal
zones: 25 $\mu g/m^3$ as annual average, and 50 $\mu g/m^3$ as 24-average.
In order to maintain full production at most sites, SO_2 concentra-
tion should not exceed 50 $\mu g/m^3$ as annual average, or 100 $\mu g/m^3$
as 24-average.

4.6.2 Photochemical oxidants[*]

The major phytotoxic components of the photochemical oxidant system
are ozone and peroxyacetylnitrate (PAN), but there is indirect evi-
dence that other phytotoxicants are present. Considerable effort
has gone into studies with controlled exposures to ozone and into
field investigations. Leaf stomata are the principal sites for
ozone and PAN entry into plant tissue. Closed stomata will protect
plants from these oxidants. Both ozone and PAN may interfere with
various oxidative reactions within plant cells. Young leaf tissue
is more sensitive to PAN, while newly expanding and maturing tis-
sue is most sensitive to ozone. Light is required before plant
tissue will respond to PAN; that is not the case with ozone.

Oxidant reduce yields of many plants, especially sensitive culti-
vars. Chronic exposures to concentrations between 100 and 300
$\mu g/m^3$ will reduce soybean, corn, and radish yields. The threshold
appears to be between 100 and 200 $\mu g/m^3$ for some sensitive culti-
vars, well within values monitored in North America and Europe.
Growth or flowering effects on carnation, geranium, radish, and
pinto bean have been found at chronic exposures to ozone at 100-
300 $\mu g/m^3$.

Mixtures of ozone and SO_2 can cause effects below the levels
caused by either gas alone; however, there is some disagreement
concerning the interactions of ozone with other gases. Ratios of
gas mixtures, intermittent exposures, sequential exposures to
pollutants, and predisposition by one pollutant to the effects of
a second pollutant may be important factors in nature, but know-
lendge is insufficient for elucidation of effects (U.S. Environ-
mental Protection Agency, 1978b).

[*]In part adapted from U.S. National Academy of Sciences (1977).

4.7 Materials

The two subjects discussed here are the impact of sulphur dioxide on metals, paints, sandstone and limestone, and the impact of photochemical oxidants on synthetic materials.

4.7.1 Sulphur dioxide*

The rate of atmospheric corrosion depends on the interaction of different climatic parameters. The most important of these are humidity conditions, temperature and the level of atmospheric pollutants. Among atmospheric pollutants, sulphur compounds cause the most damage except in coastal areas, where chlorides are also a significant factor.

The corrosion rate of carbon steel has been studied in several investigations both on a national and international basis. In all of these studies, considerably higher corrosion rates of carbon steel were found in urban and industrial atmospheres than in rural atmospheres, which indicates that the mean sulphur dioxide level constitutes a measure of the corrosivity of the atmosphere.

Several investigations have shown that the corrosion rate of zinc is strongly influenced by the atmospheric concentration of sulphur compounds.

Field tests of copper and its alloys show that corrosion rates are usually low, though they are significantly higher in urban than in rural atmosphere.

Investigations of the atmospheric corrosion of aluminium and its alloys have shown that the general corrosion is practically negligible, while a certain pitting occurs in the early stages. This pitting usually ceases before the materials have suffered any real damage. Thus aluminium has good resistance to corrosion in atmospheres polluted by sulphur compounds.

*Adapted from U.N. Economic Commission for Europe (1980).

With regard to anti-rust painted steel, paint contains both pigment
and vehicle. Together they enhance the attractiveness of the sur-
face and protect the underlying material from corrosion and
weathering. Air pollutants may counteract both of thse functions
by damaging the protective coating and by exposing the underlying
surface to corrosion. This corrosion weakens the adhesive proper-
ties of the paint.

It has been shown that coats of paint of corresponding type have
a life of about 10 to 12 years in a rural atmosphere, but about
eight years in an urban atmosphere. The difference in the rate
of deterioration must be ascribed in the main to differences in
the content of atmospheric pollutants.

Sandstone and limestone have in the past often been used for
building structures, such as churches, castles and government
buildings. They have also been used for decorative purposes on
portals, facades and for ornamentation. Such buildings and
decorations very often have a substantial cultural value, the
loss of which cannot be estimated in economic terms.

When sulphur compounds are absorbed on these surfaces a series of
reactions begins with gypsum (calcium sulphate) as the end product.
Gypsum which is more soluble than calcium carbonate, is then
washed away by rain. Other factors which can cause deterioration
is the increase in volume that takes place when calcium carbonate
reacts to form gypsum, and variations in temperature and frost.
Practical experience shows that sandstone, containing calcium
carbonate as binder, and limestone corrode at a substantially
higher rate in a sulphur polluted than in a rural atmosphere.
However, quantitative data on the relation between the corrosion
rate of sandstone and limestone and the associated level of sul-
phur pollution are still lacking.

Electrical switching devices, particularly copper, silver and gold
contacts show increased failure in polluted areas, where high
amounts of deposited sulphates, chlorides and nitrates have been

found on the metal surfaces. The corrosion is probably due to a synergistic effect of H_2S, SO_2, NO_x and chlorides.

4.7.2 Photochemical oxidants*

Ozone is a major factor in the overall deterioration of several different types of organic materials. In fact, certain specific organic compounds are more sensitive to ozone attack than are humans or animals. The magnitude of damage is difficult to assess because ozone is one of many oxidizing chemicals in the atmosphere that contributes to the weathering of materials. Neverthleless, researchers have shown that ozone accelerates the deterioration of several classes of materials, including elastomers (rubber), textile dyes and fibers, and certain types of paints and coatings.

Although many organic materials have been shown to be susceptible to ozone attack, only certain paints, elastomers, and dyes sustain damage representing significant economic loss. Even the measures to prevent ozone damage to elastomers and dyes constitute a major cost.

*Adapted from U.S. Environmental Protection Agency (1978b).

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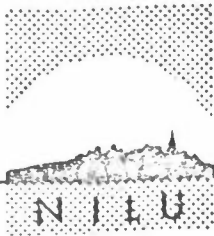

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På oppdrag fra OECD er det gitt en beskrivelse av spredning og virkninger av luftforurensninger fra varmekraftverk basert på fossilt brensel. Følgende stoffer er omtalt: Svoveloksyder, nitrogenoksyder, organiske stoffer, kvikksølv, kadmium og karbondioksyd. Følgende virkningskategorier er beskrevet: Helse, siktbarhet, klima, vannkvalitet og fisk, jordsmonn, vegetasjon og materialer.

TITLE

ABSTRACT (max. 300 characters, 5-10 lines)

As a part of the OECD "Compass" project, six important air residuals from fossil fuel energy production are discussed with respect to atmospheric pathways and impacts. The residuals are: Sulphur oxides, nitrogen oxides, organic compounds, mercury, cadmium and carbon dioxide. The following impact categories are treated Health, visibility, climate, water quality and aquatic lifte, soil quality, vegetation, and materials.

**Kategorier: Åpen - kan bestilles fra NILU   A
Må bestilles gjennom oppdragsgiver B
Kan ikke utleveres   C