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(DRAFT)

Evaluation of Health Risks of Atmospheric Pollutants

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Evaluation of health risks of atmospheric pollutants

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1 Introduction

The Commission of the European Communities, in a cooperative program with the US Department of Energy, is developing an accounting framework for identifying and quantifying the external costs associated with fuel cycles.

The initial phase consisted of the development of a general methodology (cf. bibliography). This methodology is based on :

- * an analysis of the different stages of a fuel cycle and an estimation of pollutants emissions,
- * a modelisation of transport and chemical transformation of pollutants from sources to receptors (impact pathways),
- * a modelisation of physical effects supported by receptors (human population, crops, materials) depending on their exposure,
- * a monetary valuation of physical effects.

INERIS has participated to the implementation of this methodology in France for the fossil fuel cycles (coal, oil, natural gas) in the context of the production of electricity.

As part of this programme, it has been tried to evaluate some of the effects on public health of sulphur dioxide (SO₂), nitrogen oxides (NO_x) and particulate matter emissions by generation plants.

Two directions have been privileged in the approach :

- * to present the principles of the evaluation in simple terms, understandable by a non-specialized public ;
- * to put in evidence the fundamental parameters of the phenomena and the nature of the related uncertainties.

2 Background

Observation of the harmful effects on human health, plants and building materials of smoke from combustion is almost as old as the use of fossil fuels. Thus as far back as 1273, Edward 1st published an edict prohibiting the use of coal in London because of the danger it posed to health. In fact, this ban, although renewed, failed to be applied. Pollution in London, again, in the fifties of our own century, which on one episode reached such proportions that thousands died in only a few days, contributed greatly to our awareness today of environmental problems.

The first studies on the cost of the effects of atmospheric pollution were carried out at the same time as the theoretical research on social costs conducted by A.C. Pigou at Cambridge University (*Wealth and Welfare*, 1912, and *The Economics of Welfare*, 1920).

- * The first study made of the effect of pollution on the cost of maintaining a building complex (Pittsburgh) dates back to 1913. A similar study was conducted in Manchester in 1918.
- * An evaluation of the cost of damage to harvests caused by sulphur dioxide was carried out in 1949 in the Columbia River Valley (USA).
- * A French study (G. Pannetier, 1957), quoted in a work published by the World Health Organization (WHO), estimated the cost of pollution at 6000 French francs per head of population per year, a quarter of this sum going towards medical expenses.

Today, in Western Europe, atmospheric pollution caused by smoke from combustion plants is very different from what it was at the time when the foregoing studies were being conducted. As regards sulphur dioxide and particles in particular, the concentrations commonly observed in the air are very much lower than the levels they might have reached in the past in certain industrial areas or major conurbations.

Air quality standards, expressed in terms of maximal admissible concentrations of the principal pollutants, have been laid down and are periodically revised in the light of new scientific knowledge. Compliance with these standards is designed to protect the population from the dangers that pollution can mean for public health; and generally speaking, standards are complied with. Thus an institutional approach should in principle lead to an absence of health risk - and thus of associated external costs - from the emission of particles or of sulphur dioxide in the present environmental context.

New information, which epidemiological research has been providing for the last few years, does however tend to question a number of hypotheses on which current standards are based. It suggests that, even at the concentrations currently encountered in the ambient air, there is a measurable effect of pollution, notably acid particles, on human health.

Translating these new data into external costs, associated, for example, with fuel combustion, raises two problems. First, that of determining, in the complex phenomenon of air pollution, exactly what are the factors (e.g. chemical compounds) whose presence constitutes a risk and evaluating their harmful effects. The second problem is that of assessing to what extent a combustion plant contributes to exposure of the population to this risk factor.

3 Harmfulness of particulate pollution

Two types of epidemiological approach may be adopted to reveal the effect of atmospheric pollution on public health: time-series analyses and horizontal analyses. The former deal with a region; the level of pollution is assumed to be uniform in space and variable in time; an attempt is made to see whether there is a statistical relationship between (a) atmospheric concentration values in respect of SO₂, particles in suspension, etc. measured for a short period (one or more days); and (b) levels of morbidity or mortality observed over the same period or else with a short time gap. Horizontal studies, on the other hand, monitor an average situation over a long period and compare mortality or morbidity in areas subjected to different levels of pollution. The population as a whole within an area is included ("ecological" study), or selected individuals whose characteristics are known are monitored ("cohort" study).

3.1 Data of time-series epidemiological studies

A considerable number of studies of this type have been conducted, especially in the United-States (cf. The Harvard School of Public Health Programme), dealing with large populations (for example, monitoring of the daily mortality rate among 10 million inhabitants over 10 years) in varying climatic contexts with different pollution structures. Such studies reveal notably the existence of a constant statistical relationship between different measurements of particle pollution and the daily mortality rate together with indicators of morbidity such as hospital admissions or consultations for respiratory complaints.

Such observations had already been carried out in the past. What is new, is that it has been possible to observe a relationship between air quality parameters and morbidity indicators to include levels of particle pollution which had previously been regarded as low and which are appreciably inferior to the usual air quality standards in respect of the ambient air.

Similar studies have been carried out in France, notably as part of the ERPURS Project (Evaluation of the Risks of Urban Pollution for Health). The first data were published recently (see Bibliography). On a more modest statistical basis, these data reveal relationships analogous to those observed the other side of the Atlantic.

The measured quantitative relationship between atmospheric pollution and, for example, mortality varies according to the study ; that is to say, according to the site and the method of statistical processing used. If we take ten or so American studies published since 1990, it can be seen that the mortality rate observed in a region on a given day increases by an average of 0.1% each time the particle concentration of the air (PM₁₀ particles of a size inferior to 10 µm) increases by 1 µg/m³. The ratio observed in different studies varies from 0.07% to 0.16%, this range also representing the "95% confidence level" of the ratio calculated by the major study (Philadelphia).

If the base mortality rate of a population is in the order of 1 death per year per 100 inhabitants, the foregoing relationship can be expressed by saying that 1 additional death is observed when 100,000 inhabitants are exposed for 1 year to a particle concentration increase of $1 \mu\text{g PM}_{10}/\text{m}^3$. It can then be said that "acute harmfulness" from the particle pollution revealed by these studies is in the order of 10^{-5} deaths per inhabitant. year. $\mu\text{g PM}_{10}/\text{m}^3$. To illustrate the potential significance of this concept, particle pollution measurements taken in France give average "black smoke" concentrations of generally between 10 and $40 \mu\text{g}/\text{m}^3$.

On the basis of the same principle, some American studies (Ostro, Krupnick, etc.) monitored a population sample and studied the statistical relationships between variations in time of particle pollution and the appearance of symptoms such as respiratory problems or the inability to work. Thus measurements, in a specific context, have been taken of "respiratory discomfort" acute harmfulness of 0.46 days with respiratory symptom per inhab. yr. $\mu\text{g PM}_{10}/\text{m}^3$ and "reduced work potential" acute harmfulness of 0.05 days at lowered activity per inhab. yr. $\mu\text{g PM}_{10}/\text{m}^3$).

3.2 Data of horizontal epidemiological studies

The studies referred to above attempt to evaluate acute harmfulness, i.e. an immediate effect of atmospheric pollution (instantaneous level). They give no indications as regards chronic harmfulness, i.e. the cumulative effects liable to arise from long-term exposure to pollution. Every effort is being made to evaluate these chronic effects by means of horizontal epidemiological studies.

For a long time, "ecological" studies of metropolitan areas in the USA revealed a relationship between particle pollution levels and mortality rates. Such relationships, whilst they provide food for thought, do not enable direct conclusions to be drawn, as differences of pollution levels from one region to another are also related to general differences between the various geographic, economic, urban and social contexts which may themselves help to explain divergent mortality rates.

Cohort studies, although more costly, provide increased control of factors likely to be significant and have therefore been undertaken. An initial study took place in 6 American cities and monitored 8000 adults over a fifteen-year period. In addition to pollution, the study examined determining factors such as a age, sex, race, educational level, weight, the consumption of cigarettes and alcohol, professional exposure and so on. It revealed, beside the influence of these factors, a strong statistical relationship between particle pollution, in particular a fine fraction of $\text{PM}_{2.5}$, (particle size inferior to $2.5 \mu\text{m}$) and mortality rates. The increased mortality recorded in the worst-polluted cities was due to death from cardiopulmonary diseases. Furthermore, there was an appreciably higher incidence of bronchitis and chronic coughs in these cities.

A wider study is currently in progress, embracing 151 American towns and cities and designed to monitor 500,000 adults over 7 years. The initial results published confirm those of the previous study; they would lead to an evaluation of chronic harmfulness from particle pollution in the order of 8.10^{-5} deaths per inhab. yr. $\mu\text{g PM}_{2.5}/\text{m}^3$ (standard deviation of the evaluation $1.4.10^5$). The difference between this value and that given for acute harmfulness can be partially explained by the choice of a different pollution indicator : $\text{PM}_{2.5}$ concentrations represent on average 60% of PM_{10} concentrations, thus harmfulness is revealed as 1.6 times greater. In addition, it would mean that the incidence of chronic harmfulness is approximately 5 times higher than that of acute harmfulness.

3.3 Discussion

Overall, these evaluations should, needless to say, be regarded with some caution. Observation of a statistical relationship between two variables does not imply a direct causal relationship between them. It is always possible that the relationship can be explained, partially or totally, by a third variable, correlated with each one of both.

Thus in the case of time-series analyses, we know that both the mortality rate and the level of pollution vary according to weekly and seasonal cycles, the weather and other factors. The value attributed to acute harmfulness from pollution varies according to the method used to adjust it in relation to seasonal variations and other influences; and there does exist a danger of both over- and under-correction. However, when studies conducted in different climatic contexts, using different methods to process cyclic phenomena, continuously reveal a relationship between atmospheric pollution and health, the hypothesis of a single statistical artifact becomes somewhat improbable.

The evaluation of chronic harmfulness raises even more difficult problems. Pollution is only one of a number of factors that influence mortality ; for example, its effect is outweighed by that of smoking. Thus inappropriate evaluation of the effects of the foregoing individual factors can skew the evaluation of the effect of pollution. Other factors which are not explicitly taken into account in the statistical analysis and which are possibly correlated with the level of pollution could be significant . A sedentary way of life is such a factor ; another such factor is the level of pollution during previous decades, generally much greater than the current level of pollution.

In fact, the chronic effects of pollution on health can only be measured to the extent that all the principal factors are controlled. Current data provided by epidemiological research must therefore be regarded as provisional indications. Nevertheless, their convergence and consistency lend credibility to the hypothesis of the effect of atmospheric pollution on health at commonly encountered concentrations. However that may be, considering the magnitude

of the differences of mortality rates between regions, to explain these differences is a challenging research objective.

For the rest, epidemiological studies cannot at the present time identify accurately which components or characteristics of pollution are determinant in respect of effects. Indeed, such studies can only include parameters used for the purpose of routine measurements. Furthermore, variations in these parameters are themselves very often correlated and therefore it is difficult to measure the respective influence of each one. Depending on the study, the indicator most closely correlated with health may therefore be particle concentrations (TSP, PM₁₀, PM_{2.5}, black smoke, etc.), or again sulphate, ammonium radical or H⁺ concentrations and so on. This is matter not of contradiction but of indeterminacy. It would seem, however that a factor of harmfulness is more particularly related to the particle phase, especially to the fine fraction component of this phase.

The toxicological approach, complementary to epidemiology, cannot at the present time remove this indeterminacy. The determinant parameter of harmfulness has yet to be identified : mass, number, area, chemical nature of particles, and other factors. It has still not been determined by which mechanisms relatively low particle pollution levels might cause acute cardiopulmonary complaints liable to cause the early death of a patient.

It is evident that fine particles, since they penetrate deep into the lungs and settle there, can represent a highly active impact vector ; research is being carried out to determine which processes would be likely to exacerbate drastically the condition of certain already weakened subjects. Some hypotheses point to ultrafine particles (size less than 0.01 µm) whose overall mass is low but which are very numerous. Others lay the fault at the door of oxidants (notably hydrogen dioxide H₂O₂), the concentrations of which in the ambient air correlate with particle concentrations and which may be dissolved in the aqueous phase of these particles. Still other hypotheses involve iron ions which may be fixed to the surface of the particles. It is not impossible that several pollutants are active, or that there exists a synergetic effect. It is to be hoped that certain toxicological studies taking in all these different hypotheses will bear fruit.

4 Health effect of particulate pollution caused by a combustion plant

In order to relate an effect on health and an external cost to the operation of a combustion plant, we have (a) to accept that one or another observed statistical relationship, for example between mass particle concentration and mortality or morbidity, expresses causality, and (b) to calculate the increase of particle concentrations in the ambient air resulting from combustion plant operations.

Following the previous discussion, it is clear that the first term of this approach implies a risk of error which it is difficult to quantify. It would seem to be a question of a pragmatic approach which, on the basis of the principle of precaution, could highlight what is potentially involved.

4.1 Origin of particle pollution

Particle pollution of the ambient air, as measured for the purposes of epidemiological studies, consists of three components whose relative influences are commonly of comparable orders of magnitude:

- * Dust from the ground, raised by the wind or by traffic, and possibly dust which has settled on the ground and then once again put back in suspension. Dust of natural terrestrial origin is usually of a relatively coarse grain size; it is regarded as relatively less harmful to health because generally it is arrested within the upper respiratory tract and does not penetrate the pulmonary alveoli.
- * Fine mineral or carbon-laden dust directly given off in exhaust gases from motors and fumes from stationary combustion plants or by certain industrial processes.
- * Secondary particles caused by formation in the atmosphere, from gaseous pollutants (SO_2 , NO_x , NH_3 , COV, etc.), through chemical conversion, condensation or adsorption, of chemical compounds in the form of aerosols (ammonium nitrates or sulphates, organic particles and so on).

Thus coal combustion, like the combustion of other fuels, generates an atmospheric load of particles, consisting on the one hand of particles expelled directly in smoke in a solid state (primary pollution); and on the other hand, salts (sulphates and nitrates) produced subsequently by the conversion of gaseous pollutants.

Fine particle pollution circulates and is dispersed into the atmosphere over great distances as it penetrates, moreover, closed premises. In order to evaluate the overall effect of an emission, one has to consider the resultant increases in particle concentration in a very large area of influence around the point of discharge; if we take France as an example, we should have to consider an area taking in the entire continent of Europe.

4.2 Exposure of a population to the pollution generated by an emission

For a given individual, the risk to health engendered by atmospheric pollution - that is, the probability of a respiratory disease or of death - is assumed to be proportional to both the harmfulness of the pollutant and the amount of the pollutant absorbed by the individual. This second term is itself proportional to the concentration of the pollutant in the ambient air and the time during which

the individual is exposed to this concentration ; exposure of the individual is referred to as the product of these two factors.

In the case of a population, the collective exposure is the sum total of exposure of the individuals making up the population. The overall effect of an emission is thus the product of harmfulness multiplied by collective exposure.

The collective exposure caused by the emission, at a given place and time, of a puff of pollutant depends on the location of the population and also on the diffusion of the pollutant in the atmosphere, its chemical evolution and its deposition on the ground. These processes obey complex physical laws which, in some cases are not fully understood and which models are being used to elucidate. The sophisticated nature of certain models cannot disguise the fact that the real values of the base parameters (rate of deposition, the kinetics of the chemical reactions) are often imperfectly grasped. Given the magnitude of the various uncertainties, we shall refer, in order to illustrate a "standard" situation, to very simplified models.

Using a model of this sort on a large scale, it can be shown (see Appendix) that the collective exposure resulting from pollution within a given geographical area is the product of three factors : the mass of pollutant falling on the area concerned, average population density per unit of ground surface area, the inverse of the deposition velocity of the pollutant on the ground.

The model in question assumes that the "emitters" and "receivers" of pollution are distributed uniformly or at least independently over the area concerned; if this is not the case (emissions in an urban environment), we need to include an additional term: over-exposure to the primary pollution. This additional term depends on the size of the conurbation, population density and average wind speed within the area.

4.3 Effects on public health of a combustion plant

On the basis of a hypothesis of harmfulness and of an exposure model, we can calculate, for example, the effect of a coal combustion plant. The effect will depend mainly on the following :

- * the properties of the coal (e.g. sulphur content) ;
- * the characteristics of the plant (particles removal from the combustion gases, desulphurization, control of the production of nitrogen oxides, etc.);
- * the emission site (especially in the case of emission within a conurbation).

Tables 1 to 6 illustrate the calculation. The social costs appear considerable in certain scenarios, whether worked out per tonne of pollutant, ton of coal or kWh of electricity. It will be noted, for example, that these are comparable, in order of magnitude, to certain measures designed to prevent the discharge of harmful emissions.

4.4 Aspects requiring further research

Earlier emphasis was placed on the uncertainty associated to the value of the harmfulness of atmospheric particulate pollution. The hypothesis considered in the example above refers to American time-series analyses and the relationship PM_{10} /acute harmfulness. A hypothesis based on the relationship $PM_{2.5}$ /chronic harmfulness would lead to evaluations of the effects in terms of mortality rates and the corresponding external costs, multiples of a factor 8 of those shown in the table. Conversely, if one assumes that an increase in concentration is only harmful where the concentration exceeds a certain threshold, the estimated effects would be lower ; for example, if effects were restricted to urban areas, they would be divided by a factor of the order of 2.

Other uncertainties are related to the calculation of exposure :

- * As regards direct particle emissions, the statutory standards provide a reference point (an emission ceiling) ; but there is incomplete knowledge of actual particle emission according to the coal used and the various types of plant (combustion, dust removal, etc.); particle size distribution in particular has a major influence on the deposition velocity.
- * Concerning large-scale pollution dispersion and the formation of secondary particles, the purpose of the calculations shown is to highlight the principal parameters of the problem ; the values used for these parameters are rough estimates. A more realistic evaluation should be based on a number of studies such as those conducted under the European EMEP Programme (Co-operative Programme for Monitoring and Evaluation of the Long Range Transmission of Air Pollutants in Europe).
- * Evaluation of the mass of nitrate particles produced by the emission of nitric oxides poses a special problem: there is in effect a balance in the atmosphere between nitrate of ammonium particles and nitric acid and ammonia gas. This balance depends on temperature, humidity and the composition of the atmosphere. In the calculation shown here, it has been assumed that 50% of the NO_3 radicals present in the atmosphere are in the form of particles ; this is a provisional hypothesis which will require further research.
- * As regards the additional term for emissions in an urban area, the proposed model has the advantage of very easy operation. However, as far as we are aware it has not been tested or parameterized in the french urban context.

In expressing the results in terms of external costs, the level of unit costs applied in respect of morbidity and mortality is obviously a major factor. The

unit costs of a "day of discomfort" or a "day of reduced activity" are those adopted for the ExternE European Programme. The unit cost attributed to a death refers to french studies on road safety. If for example we applied in the case of this unit cost the value proposed by the ExternE study, the external cost of mortality would be multiplied by a factor of 5.

5 Conclusions

To date, science has only an incomplete knowledge of all the direct and indirect effects that industrial activities have on the environment. Any attempt to evaluate the risks and the associated environmental costs of a given activity is therefore necessarily incomplete.

Certain effects such as the effect on health form the classic subjects of evaluation in respect of external costs. Such evaluations, given the complexity of the systems involved, inevitably remain subject to uncertainty.

The example proposed here shows that the results of calculating the external costs only make sense if the hypotheses on which they are based are fully explained and discussed. It also shows that a major effort is required in order to reduce the margin of uncertainty that accompanies these calculations at the present time.

It remains to say that evaluating external costs presuppose clarification of all current knowledge in respect of the effects of an industrial sector or activity on the environment. It provides a challenging framework for multidisciplinary research.

Bibliography

European Commission, Directorate-General XII, Externalities of fuel Cycles, "ExternE" Project, Coal fuel Cycle, prepared by ETSU, U.K., IER, Germany, 1994.

A. Rabl, G. Landrieu, et al., Environmental Impacts and Their Costs : the Nuclear and the Fossil Fuel Cycles, Final report of the project "External Costs of Fuel Cycles : Implementation of the Accounting Framework in France" funded by the European Commission DG XII (february 1995).

Ministère des Affaires Sociales, de la Santé et de la Ville, Conseil Supérieur d'Hygiène Publique de France : Particules en suspension dans l'atmosphère ; effets sur la santé et proposition pour une révision des valeurs limites, Paris 1993.

ERPURS, Impact de la pollution atmosphérique urbaine sur la santé en Ile-de-France, Observatoire Régional de Santé d'Ile-de-France, Paris 1994.

Proceedings of the Colloquium on Particulate Air Pollution and Human Mortality and Morbidity, *Inhalation Toxicology*, Volume 7 Number 1, 1995.

C. Arden Pope et al., Particulate Air Pollution as a Predictor of Mortality in a Prospective Study of U.S. Adults, *Am J Respir Crit Care Med* 1995 ; 151 : 669-74.

APPENDIX

Brief outline of methodology : some simple models used to evaluate collective exposure related to the discharge of pollutants into the atmosphere

Dispersion of pollutants in the atmosphere, their chemical evolution as a function of meteorological factors and the presence of other components, and their deposition on the ground obey highly complex physical laws. A number of simple models can, however, be used to ascertain the principal parameters in respect of these phenomena and the extent of the effects.

1 Large-scale model of dispersion in an infinite space

The earth's surface is represented by an infinite plane space. One has to imagine receivers located on the surface of this plane space and sensitive to atmospheric pollution ; for example, a population of Δ uniform density.

Let us take the emission of a "puff" of pollutant, with Q the quantity of the pollutant emitted. The pollutant disappears progressively from the atmosphere with time ; T is the average time during which the molecules of the pollutant remain in the atmosphere.

The assumption is that dispersion of the pollutant is restricted to a lower part of the atmosphere, where there is very considerable turbulence and which is known as the mixed layer. The height h of the mixed layer is constant ; at a given time and in a given place, the pollutant concentration is equal at different altitudes in the mixed layer.

On the basis of the foregoing hypotheses, it can be seen that the collective exposure resulting from the puff of pollutant, from the instant of emission to the moment where the pollutant has completely disappeared, can be expressed as follows :

$$E = \Delta Q T \frac{1}{h}$$

2 Removal of the pollutant by deposition on the ground

Let us consider the case of a stable pollutant, that is to say one that is chemically inert in the atmosphere. It can only disappear by deposition on the ground, either directly in dry conditions or under humid conditions (carried by rain, fog, snow).

The deposition velocity V is defined as the ratio between the mass of pollutant which settle in a given place per unit of surface area and per unit of time and the concentration of the pollutant in the atmosphere directly above the place concerned.

The deposition velocity of a pollutant is an empirical parameter analogous to the sedimentation velocity of particles. We shall consider here an average deposition velocity and assume it to be constant, taking into account both dry and humid deposition.

The pollutant is eliminated from the atmosphere by deposition at a constant rate per unit of time $\lambda = \frac{V}{h}$. The average time the pollutant remains in the atmosphere is :

$$T = \frac{h}{V}$$

The foregoing model can be simplified and expressed as follows:

$$E = \Delta Q \frac{1}{V}$$

3 Exposure to a reactive pollutant

As well as deposition on the ground, the pollutant contained in the puff disappears due to chemical reactions in the atmosphere. This process can often be modelled by a "first order" law : the quantity of pollutant consumed by the reaction per unit of time and unit of volume is proportional to the concentration of the pollutant which remains present in the atmosphere at a given time. The pollutant is eliminated from the atmosphere by chemical reaction at a constant rate per unit of time μ .

The quantity of pollutant emitted Q divides into a mass D deposited on the ground and a mass R which disappears due to chemical reaction. Thus we have:

$$D = \frac{\lambda}{\lambda + \mu} Q \quad ; \quad R = \frac{\mu}{\lambda + \mu} Q$$

Collective exposure may be expressed as follows:

$$E = \Delta D \frac{1}{V}$$

4 Secondary pollutant

The above formulae also account for exposure to secondary pollution, if we consider Q as the amount of secondary pollutant produced from a mass Q_P of a primary compound.

Let λ_P be the rate of elimination by deposition of the primary compound, μ_P the constant of reaction, R_P the mass of the primary compound that reacts, σ the stoichiometric coefficient (mass of secondary pollutant generated by the reaction of a unit mass of the primary compound). This gives:

$$Q = \sigma R_P = \sigma \frac{\mu_P}{\lambda_P + \mu_P} Q_P$$

5 Collective exposure induced in a delimited geographical space

If we retain the foregoing hypothesis, we can specifically consider collective exposure $E_{\mathcal{R}}$ of receivers located in a space \mathcal{R} representing, for example, one country or a group of countries.

Let $\Delta_{\mathcal{R}}$ be the density of receivers in the area \mathcal{R} and $D_{\mathcal{R}}$ the total mass of pollutant deposited in this area. We then have:

$$E_{\mathcal{R}} = \Delta_{\mathcal{R}} D_{\mathcal{R}} \frac{1}{V}$$

If $P_{\mathcal{R}}$ is the total population of the region and $S_{\mathcal{R}}$ its surface area, we can use the following formula :

$$E_{\mathcal{R}} = P_{\mathcal{R}} \frac{D_{\mathcal{R}}}{S_{\mathcal{R}} V}$$

The factor $\frac{D_{\mathcal{R}}}{S_{\mathcal{R}}}$ is the average deposition of pollutant per unit of surface area in the region, the term $\frac{D_{\mathcal{R}}}{S_{\mathcal{R}} V}$ the integral in the time of a concentration.

Evaluation, in a real situation, of that part of an emission which is deposited in a given area assumes in principle that the circulation of air masses in the atmosphere are known. This means using complex meteorological models such as those developed under the European EMEP Project.

However, if we take a puff of pollutant emitted within a given site, e.g. France, and which circulates above a given area, e.g. Europe, before escaping to others countries or to sea, it will be observed that, if we apply the foregoing hypotheses, the mass of pollutant deposited, and thus collective exposure, only depends on the duration of the path above Europe.

EMEP shows, for example, that in the case of emissions of sulphur dioxide, nitrogen oxides and ammonia, the percentages of sulphur and nitrogen falling out over Europe are respectively 64%, 52% and 82%. On this basis, it is possible to reconstruct approximately the distribution of the duration of the path over Europe of french emissions and so evaluate simply the levels of exposure to different pollutants.

6 Emission in an urban context : additional term for collective exposure to primary pollution

The hypothesis of a homogeneous mixture of pollution over the full height of the mixed layer is not valid near the source of the pollution. Local exposure

requires to be studied specifically, especially when receiver density, instead of being uniform, is characterized by clusters and emission is located within a cluster.

Given the limited time the pollutant remains near the point of emission, the phenomena of deposition and chemical conversion of the pollutant are not taken into account. The only vector of elimination of the pollution is the wind.

A classic model for calculating the average concentration of a pollutant in an urban area is the ADTL model, a simplified result of a gaussian representation (Atmospheric Turbulent Diffusion Laboratory, Hanna 1971). This model shows that the term E_L of local exposure depends on the density of the urban population Δ_L on the quantity Q of the primary pollutant emitted and average wind speed U :

$$E_L = \Delta_L Q \frac{K}{U}$$

The form of this expression is similar to that of the base model, provided the parameter V is replaced by $\frac{U}{K}$. The coefficient K is interpreted as the ratio of the length of the urban area to the average height up to which the pollutant is diffused over the urban area. Average height itself depends on the size of the conurbation as well as on meteorological factors (atmospheric stability). Coefficient K also varies, in practice, according to the conditions under which the pollutants are emitted : it is lower in the case of a pollutant of which a large proportion is discharged by tall chimneys (SO_2) and higher with a pollutant discharged at ground level (CO).

With certain types of pollution, it would be necessary to take into account other stages of overexposure associated with other containment phenomena : pollution from cars in canyon-streets from which pollution escapes with difficulty, domestic heating appliances in enclosed premises, and so on.

Table 1 - Calculation of the masses of secondary sulphate and nitrate particles produced by emissions of sulphur dioxide and nitrogen oxides

		formulation	unit	sulphur dioxide	nitrogen oxydes
Deposition rate	(1)	λ_P	%/hour	4.3	0.7
Oxidation rate	(1)	μ_P	%/hour	1.6	3.3
Stoichiometric coefficient	(2)	σ	-	1.93	1.74
Part of the oxidised radical present in particle form	(3)	β	-	1	0.5 (prov.)
Particles mass produced per ton of primary emission		$Q = \sigma \frac{\mu_P}{\lambda_P + \mu_P} \beta$	tonne / tonne	0.5	0.7 (prov.)

Notes :

(1) The values used for deposition rates and reaction kinetics are those of the TREND model (cf. *Atm. Env.*, Vol. 23, No. 9, 1989).

(2) It is assumed that the secondary product obtained by oxidation of the sulphur dioxide consists of a mixture in equal proportions of $\text{SO}_4(\text{NH}_4)_2$ and $\text{SO}_4\text{H}\text{NH}_4$. The particulate product from nitrogen oxides is NO_3NH_4 .

(3) There is a balance in the atmosphere between particulate ammonium nitrate and nitric acid/ammonia gas. The balance depends on temperature, humidity and the composition of the atmosphere. Thus the proportion of NO_3 radicals present in the form of particles varies considerably according to the location and the season. The 50% hypothesis is provisional.

Table 2 : Calculation of collective exposure to particle pollution by emissions of fine primary particles, sulphur dioxide and nitrogen oxides. Exposure at European level. emissions in France (average case).

	formulation	unit	primary particles	sulphur dioxide	nitrogen oxides
Particle mass produced per tonne of primary emission	Q	tonne / tonne	1	0.5	0.7 (prov.)
Proportion of mass deposited in Europe (1) (2)	$a_{\mathcal{R}}$	-	0.65	0.5	0.5
Mass deposited in Europe	$D_{\mathcal{R}} = a_{\mathcal{R}} Q$	tonne / tonne $\mu\text{g} / \text{tonne}$	0.65 $0.65 \cdot 10^{12}$	0.25 $0.25 \cdot 10^{12}$	0.35 $0.35 \cdot 10^{12}$
Particle deposition velocity (1)	V	cm/s m/yr	1 $0.31 \cdot 10^6$	1.08 $0.34 \cdot 10^6$	1.61 $0.51 \cdot 10^6$
Population density	$\Delta_{\mathcal{R}}$	inhab./km ² inhab./m ²	100 $100 \cdot 10^{-6}$	- id -	- id -
Collective exposure per tonne of primary emission	$E_{\mathcal{R}} = \Delta_{\mathcal{R}} D_{\mathcal{R}} \frac{1}{V}$	inhab. yr. $\mu\text{g}/\text{m}^3$ per tonne	210	74	67 (prov.)

Notes :

(1) Knowledge of the size distribution of the primary particles present in the smoke emitted by various types of combustion plant is incomplete. The deposition velocities and the proportion of emissions from France deposited in Europe shown in the table are therefore hypothetical.

(2) Estimations concerning proportions of secondary particles deposited in Europe were obtained from analysis of EMEP results.

Table 3 - Calculation of health effects and corresponding external costs arising from emissions of fine primary particles, sulphur dioxide and nitrogen oxides. Effect at European level, emissions in France (average case).

	formulation	unit	primary particles	sulphur dioxide	nitrogen oxides
Collective exposure to particle pollution per tonne of primary emission	$E_{\mathcal{R}}$	inhab. yr. $\mu\text{g}/\text{m}^3$ per tonne	210	74	67 (prov.)
Harmfulness of particle pollution : short-term mortality (1)	N_d	No. of deaths per inhab. yr. $\mu\text{g}/\text{m}^3$	$1 \cdot 10^{-5}$	- id -	- id -
Number of deaths attributable to one tonne of primary emission	$I_d = E_{\mathcal{R}} N_d$	No. of deaths per tonne	$2.1 \cdot 10^{-3}$	$0.74 \cdot 10^{-3}$	$0.67 \cdot 10^{-3}$
Unit cost/ death (2)	U_d	francs /death	3 500 000	- id -	- id -
External cost of mortality per tonne of primary emission	$C_d = I_d U_d$	francs / tonne	7 350	2 590	2 345
Harmfulness of particle pollution : (short-term morbidity) (3)		No. per inhab.yr. $\mu\text{g}/\text{m}^3$ of			
respiratory symptoms	N_g	days of discomfort	0.46	- id -	- id -
reduced activity	N_a	days of red. activity	0.05	- id -	- id -
Effects attributable to one tonne of primary emission		per tonne, No. of			
respiratory symptoms	$I_g = E_{\mathcal{R}} N_g$	days of discomfort	97	34	31
reduced activity	$I_a = E_{\mathcal{R}} N_a$	days of red. activity	10.5	3.7	3.6
Unit costs (4)		francs per			
respiratory symptoms	U_g	days of discomfort	45	- id -	- id -
reduced activity	U_a	days of red. activity	450	- id -	- id -
External cost of morbidity per tonne of primary emission		francs / tonne			
respiratory symptoms	$C_g = I_g U_g$	francs / tonne	4 365	1 530	1 395
reduced activity	$C_a = I_a U_a$	francs / tonne	4 725	1 665	1 620
Health external cost (short-term effect) per tonne of primary emission	$C = C_d + C_g + C_a$	francs / tonne	16 500	5 800	5 400 (prov.)

Notes :

- (1) The hypothesis refers to U.S. studies on the "PM₁₀ concentrations/short-term mortality variations" relationship. A hypothesis based on a "PM_{2.5}/inter-regional mortality variations" relationship would give a harmfulness value 8 times higher.
- (2) Unit cost of death used in french studies on road safety ; the European ExternE study refers to a value 5 times higher.
- (3) Estimations of short-term effects made in an american context (Ostro. Krupnick).
- (4) Unit costs applied in the ExternE study.

Tableau 4 : Additional exposure to primary pollution from the discharge of fine particles in an area of high population density. Additional term of health external costs.

		formulation	unit	fine particles
Population density	(1)	Δ_L	inhab./km ² inhab./m ²	1000 1. 10 ⁻³
Average wind speed		U	m / s m / year	5 160. 10 ⁶
Hanna's constant	(2)	K	-	200
Exposure to a primary emission		$E_L / Q = \Delta_L \frac{K}{U}$	inhab. yr. g/m ³ / g inhab. yr. µg/m ³ per tonne	1.25. 10 ⁻⁹ 1250
Additional health external cost per tonne of primary emission		$C_L = E_L \frac{C}{E_R}$	francs / tonne	100 000

Notes :

(1) The case proposed corresponds to a population density close to that of the Ile de France.

(2) Hanna's model, developed within an American context, has not to our knowledge been the subject of adjustment studies in respect of French urban areas. It is not applicable to the case of discharge from a tall chimney. The value of the constant used here applies to a large conurbation.

Table 5 - Calculation of "damage to buildings" cost attributable to the emission of sulphur dioxide

	unit	large scale effect	Additional local effect of an emission in a densely populated urban area
Collective exposure per tonne of SO ₂ (1)	inhab. yr. µg/m ³ per tonne	150	1 250
Harmfulness of pollution by sulphur dioxide in terms of additional building maintenance costs (2)	francs per inhab. yr. µg/m ³	10	- id -
Damage to building external cost per tonne of SO ₂ emission	francs / tonne	1 500	12 500

Notes :

(1) In the context of situations described in previous tables. The value in respect of general collective exposure from one tonne of sulphur dioxide only differs from that from particles by the factor $\lambda / (\lambda + \mu) = 0.73$, since the deposition velocity of sulphur dioxide is close to that applied previously for particles. Urban overexposure is identical if it is admitted that Hanna's constant has the same value.

(2) This estimation is based on studies conducted in Dortmund, Birmingham, Stockholm, Sarpsborg and Prague. In each city an analysis was made of the costs of maintaining building complexes located in areas with different levels of pollution. Costs differences have been attributed to SO₂ concentrations differences. That hypothesis is a schematization ; others pollutants (nitrogen oxides, particles), and others factors, could explain a part of the differences.

**Table 6 - Elements of external costs
related to coal combustion plant operations.
Effects in Europe of an emission in France
Short-term effects on public health and damage to buildings**

		unit	Old plant located in an urban area	Plant with pollution control measures located outside an urban area
Emissions		kg of		
primary particles	(1)	pollutant emission	0.5	0.5
sulphur dioxide	(2)	per tonne	20	2
nitrogen oxides	(3)	of coal burnt	15	5
External cost per emission unit				
primary particles	(4)	francs / kg	116	16.5
sulphur dioxide		of pollutant		
public health		emitted	5.8	5.8
buildings			14	1.5
nitrogen oxides			5.4 (prov.)	5.4 (prov.)
Elements of the external cost of the plant				
primary particles			58	8.25
sulphur dioxide		francs		
public health		per tonne of	116	11.6
buildings		coal burnt	280	3
nitrogen oxides			81 (prov.)	27 (prov.)
Sum of external cost elements		francs per tonne of coal burnt	535	50
Electricity generating plant: Cost in terms of electricity produced :		centimes par kWh	18	1.65
	(5)			

Notes :

- (1) Combustion of pulverized coal ; use of coal with a 10% ash content ; dust removal efficiency 99.5%.
- (2) Coal with a 1% sulphur content ; desulphurization variant 90% efficient.
- (3) Variant. low-NO_x burners.
- (4) Discharge to atmosphere in an urban area is assumed to occur at a height above ground of the same order as average discharge of sulphur dioxide in an urban area.
- (5) It takes 0.33 kg of coal to produce 1 kWh.