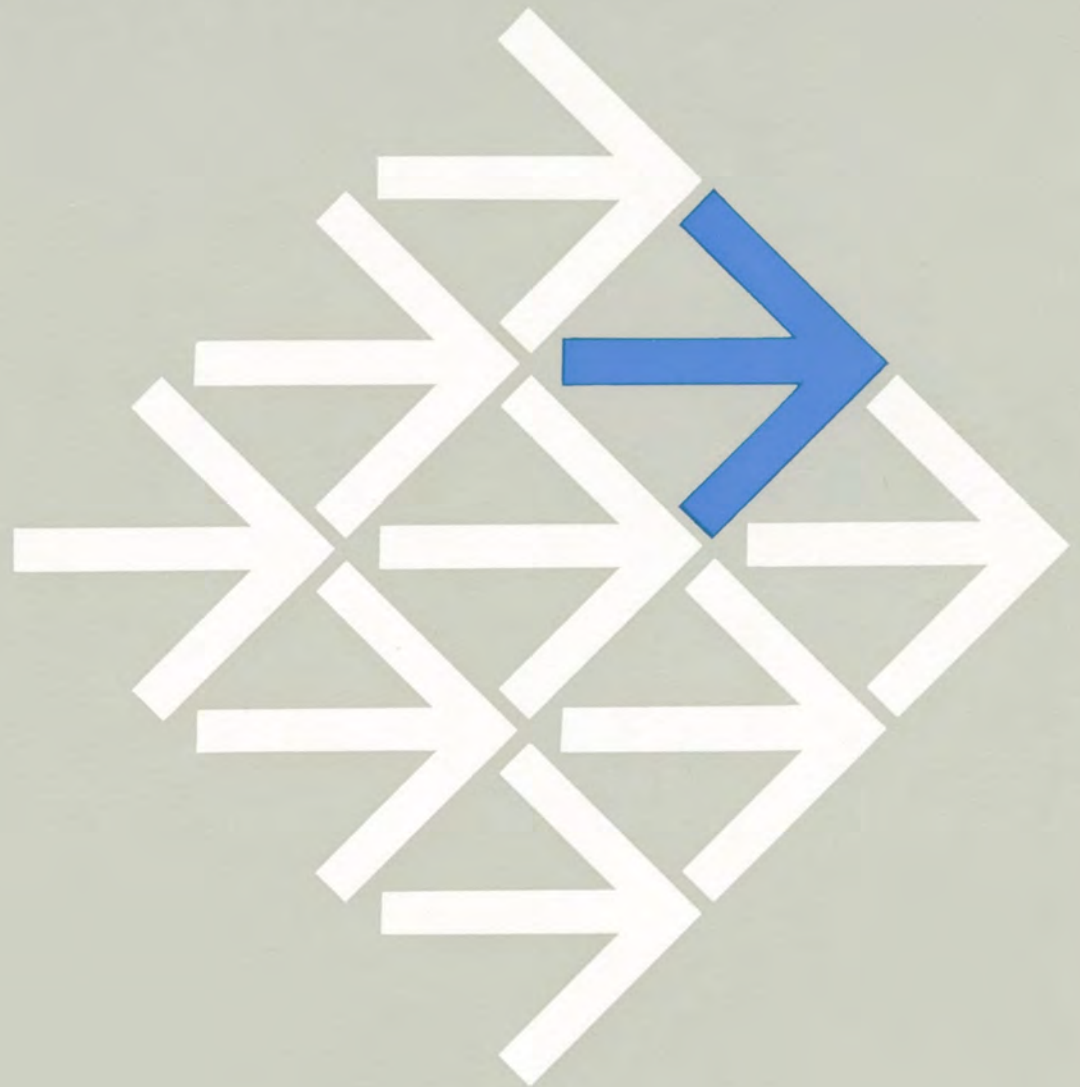


# TOEKOMSTBEELD DER TECHNIEK

FUTURE SHAPE OF TECHNOLOGY PUBLICATIONS

publicaties t.b.v. de toekomststudies

## Electrical energy needs and environmental problems, now and in the future



STICHTING TOEKOMSTBEELD DER TECHNIEK

KONINKLIJK INSTITUUT VAN INGENIEURS

The **STICHTING TOEKOMSTBEELD DER TECHNIEK** (Future Shape of Technology Foundation) was established in 1968 by the Royal Institution of Engineers in The Netherlands.

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# FUTURE SHAPE OF TECHNOLOGY PUBLICATIONS

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Number 7

## Electrical energy needs and environmental problems, now and in the future



## Preface

Electrical energy supply and environmental protection are elements of vital importance in present and future society. The growing concern over disturbances of the environment has given rise to increased interest in the system of electricity supply.

This publication is one of three dealing with future energy supply, that will all appear in 1971. It is intended to promote insight into the interrelation between the constantly growing demand for electrical energy, the ways in which this demand can be met — both now and in the future — and the resultant impact on the environment.

Electricity consumption in the industrialized nations has been doubling every ten years for several decades. This rate of growth has been caused by an increasing need for electricity in all spheres: domestic, public and industrial, apart from the influence of the population increase. There are, as yet, no indications of a slackening of growth in the demand for this convenient and — at the point of consumption — clean form of energy.

Extensions of energy supply systems have to meet joint requirements imposed by economic criteria, by the need for reliability and safety, as well as by the necessity of protecting the environment. This publication examines present technological and economic limitations and further discusses the feasibility of alternative solutions for the future. The long lead times that go with research, development and manufacture, as well as the technical/economical lifetime of the installations made it appropriate that the survey cover the next three to four decades.

Many examples used in this study are based on the situation in the Netherlands, the country with the highest power density (MW per km<sup>2</sup>) in the world. The analysis has, however, been made in such a way as to make it of more than just national importance.

This publication will provide basic technical information for the international colloquium: "Electrical energy needs and environmental problems, a case for European and international co-operation" planned for June, 1971, under the auspices of the John F. Kennedy Institute at Tilburg, the Netherlands. Considering the international context it was decided to publish this study in the English language.

A Foundation symposium dealing with more specific national problems in electricity supply in The Netherlands, is planned for autumn 1971. May this publication promote study and research, as well as national and international coordination in these fields.

L. Schepers,  
President of the Foundation Board

## Editorial Committee

The authors:

### Chapter 1

ir. J. H. Bakker and prof dr. J. J. Went,  
Directors,  
Arnhemse Instellingen van de Electriciteitsbedrijven  
in Nederland.  
(Joint Institutions and Laboratories of the Electric  
Utilities in The Netherlands).  
Utrechtseweg 310, Arnhem, The Netherlands.

### Chapter 2

dr. K. J. Keller,  
Senior physicist,  
N.V. tot Keuring van Elektrotechnische Materialen,  
KEMA.  
(Joint Laboratories of the Electric Utilities in  
The Netherlands).  
Utrechtseweg 310, Arnhem, The Netherlands.

### Chapter 3

ir. A. J. Elshout,  
Research and development officer,  
H. van Duuren,  
Chemical engineer,  
Chemical Department, N.V. tot Keuring van Elektro-  
technische Materialen KEMA.  
(Joint Laboratories of the Electric Utilities in  
The Netherlands).  
Utrechtseweg 310, Arnhem, The Netherlands.

### Chapter 4

ir. J. L. Koolen,  
Head of the Department of Surface Water,  
Rijksinstituut voor Zuivering van Afvalwater (RIZA).  
(Government Institute of Sewage Purification and  
Industrial Waste Treatment).  
Westeinde 3a, Voorburg, The Netherlands.

### Chapter 5

P. E. Joosting,  
Medical research officer and adviser,  
Instituut voor Gezondheidstechniek TNO.  
(Research Institute for Public Health Engineering  
TNO).  
Postbus 214, Delft, The Netherlands.

dr. J. C. ten Houten,  
Director, Instituut voor Plantenziektkundig  
Onderzoek.  
(Institute for Phytopathological Research).  
Binnenhaven 12, Wageningen, The Netherlands.

### Chapter 6

J. A. G. Davids,  
Biologist in the Health Protection Department,

prof. dr. J. A. Goedkoop,  
Managing Director for Research,

ir. M. Muysken,  
Mechanical Engineer charged with the coordination of  
light water reactor development,

all at Reactor Centrum Nederland, Petten (N.H.),  
The Netherlands.

### Foundation representatives:

prof. ir. D. G. H. Latzko,  
Member of the Foundation Board, President of the  
Editorial Committee.

ir. P. J. J. Blok,  
Foundation staff member, in charge of the  
coordination of this publication.

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Figure 1 - Electric power plant 'Waalhaven' at Rotterdam. Enlargement under construction. (Photo KLM Aerocarto N.V.).



# CHAPTER 1. ELECTRICAL ENERGY, DEMAND AND SUPPLY

by J. H. Bakker and J. J. Went

## Summary

*The demand for electrical energy is increasing at a still faster rate than the growth of energy consumption in general.*

*To satisfy the demand, electric power is produced mainly in thermal power stations, using fossil or nuclear fuel. This kind of production is connected with the heating up of cooling water and — for fossil fuel plants — with air pollution by combustion products.*

*Production units can be placed outside heavy populated areas, and so environmental effects can be better controlled with direct combustion of fossil fuel inside populated areas.*

*Electricity is a clean use of energy at the place where it is needed.*

*These facts may lead to a still larger growth rate of electricity consumption.*

*For future electric power production breeder and fusion reactors are evaluated. Various direct conversion methods are discussed.*

*Present-day and future transmission systems are dealt with.*

## I. General remarks on energy

The sun is the energy source that was, is and will be sufficient to make plant and animal life possible on earth for a practically infinite future. However, the civilization of mankind needed and needs a certain amount of additional concentrated energy for many purposes. This amount of energy is extremely small compared with the energy we are receiving from the sun. The thermal energy of the sun, intercepted by the earth, is about 100,000 times greater than the present-day installed electrical capacity. However, energy consumption is increasing so fast that there is a real problem with respect to the availability of this additional energy source and to the environmental aspects.

Originally, in the days when energy was required only for cooking and for some heating, wood was for a long time quite sufficient. Finally so much wood was used that deforestation had degraded many environments. For the last 150 years increasingly large amounts of coal and other fossil fuels (oil and gas) have been needed for steel manufacture and steam engines. At the end of the last century electricity as a modern form of energy was introduced.

## II. Electrical energy

With electricity it is possible to meet man's requirements for power and heat as well as for light and telecommunication. For telecommunication no other form of energy than electricity is possible, and for lighting it is by far the most efficient and simple source

of energy. For mechanical power in general, and for all mass transport (except shipping), it is equally important. However, 75 % of all energy needs are still satisfied without the intermediate link of electricity. As the growth rate of electrical energy consumption (7–12 % per year) has been twice the growth rate of energy consumption in general (3–5 % per year) for a very long time, it may be expected that the gradual increase in electricity's share of the market will eventually reach at least 50 %.

There is yet another very important reason why electrical energy should penetrate further, particularly in highly developed parts of the world. When *applying* electrical energy for one purpose or another it is a clean energy, not disturbing or poisoning the immediate surroundings of the place of application. When *producing* electrical energy somewhere, this is not always the case.

In general, electric power is generated in large units in central power stations. Apart from hydroelectric power production, which is of some importance in the present world, most electric power is produced in thermal power stations.

In these thermal power stations either fossil or nuclear fuel is used. With fossil fuel environmental effects from combustion products in the atmosphere may occur, in addition to the heating of cooling water. With nuclear fuel in nuclear fission reactors, radioactive fission products are formed. These fission products, although contained, can be a potential hazard to the surroundings. However, their quantity is so small compared to the amount of combustion products (a factor of 20 million) that their concentration and storage is technically possible. Therefore atmospheric pollution can be avoided with nuclear reactors. The storage of combustion products, on the other hand, is unrealistic; it would mean storing an amount of gases having the fourfold weight of the original fossil fuel.



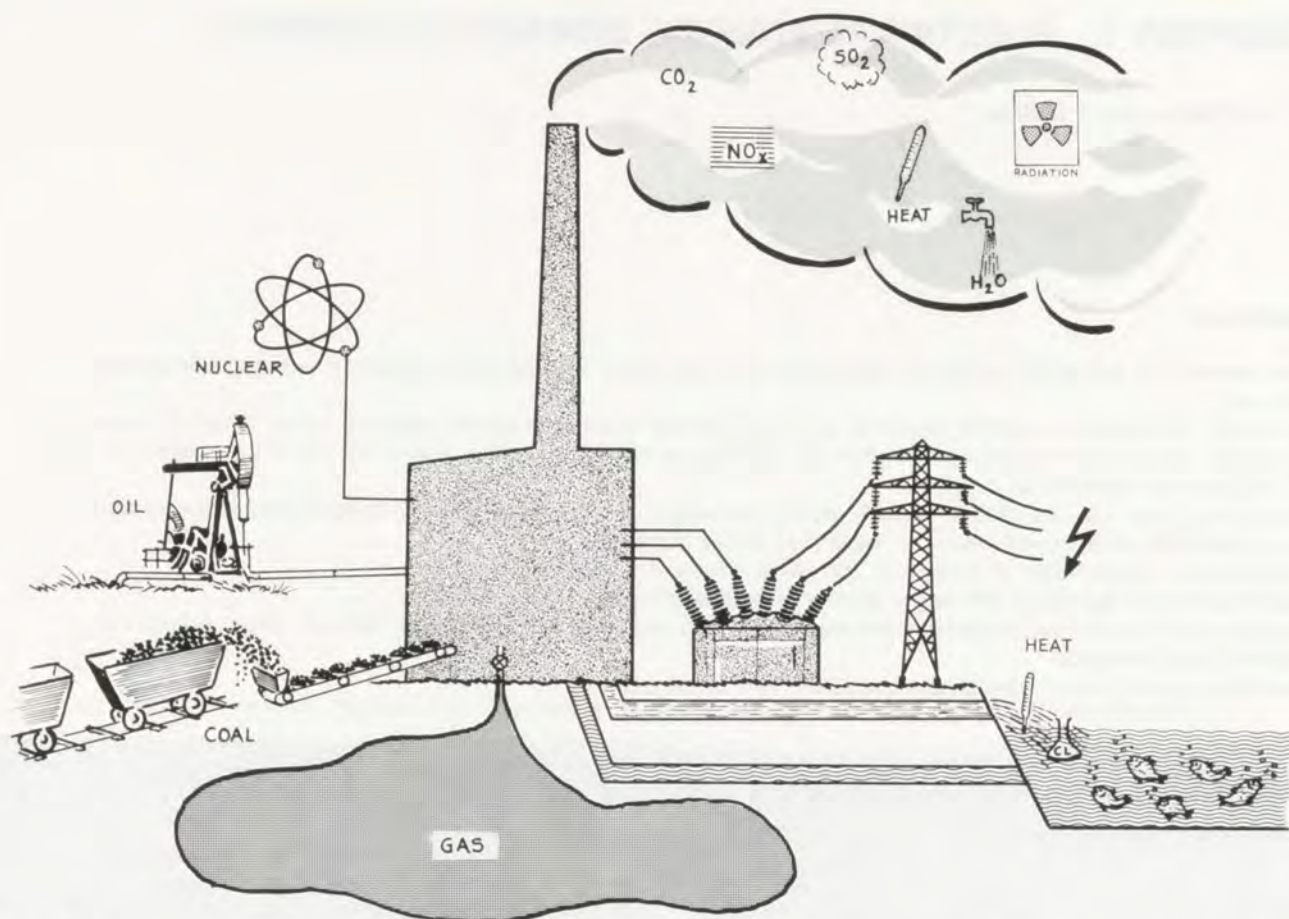


Figure 2 - Simplified diagram of a thermal power station, illustrating the input of different types of fuel and the output of electricity as well as the main waste products. (See also chapters 2, 3 and 6).

The heating of cooling water, however, is of the same order of magnitude for either fissile or fossil fuels. In modern light water nuclear steam plants the amount of cooling water required is about 1.7 times greater than for fossil fuel steam plants.

### III. The current demand for electrical energy

The demand for electrical energy is a function of the growth of the gross national product. In highly developed countries such as the United States, Canada and Sweden the demand is very high (about 8000 kWh/year/inhabitant). In the Western European countries the demand lags behind by about 10 to 15 years, consumption being about 3000 kWh/year/inhabitant. In the underdeveloped countries the electrical energy demand is still very low.

In assessing the environmental effects of electrical energy production, it is more important to know the electricity production per km<sup>2</sup> than per inhabitant. Additional important factors are the presence of a sufficient percentage of water surface per km<sup>2</sup> for cooling purposes, and the strength and directions of prevailing winds for evaluating the air pollution. In Table 1 a few data are given for 1968 for different European countries, for the EEC as a whole, and for

the United States. The countries are listed according to their thermal electricity production per km<sup>2</sup>. It is immediately clear from this table that the population density is the most important factor determining the production figure per km<sup>2</sup>.

For all countries two figures are given:

1. the thermal electricity production in GWh/km<sup>2</sup>;
2. the total electrical energy consumption in GWh/km<sup>2</sup>.

The latter figures are higher in the countries with hydroelectric energy production and are also slightly different from the first figures due to some import or export of electricity.

### IV. The future demand of electrical energy

Energy demand in the highly developed countries is growing, and has been for many decades, at a rate of 3-5 % per year.

Electrical energy consumption, however, is growing much faster: 7-12 % per year, resulting in doubling times of roughly 10 years. These doubling times have been constant for about half a century, and apply to a country such as the Netherlands with an intermediate high consumption level (about 2500 kWh/capita) as well as to the United States or Canada with about 7500 kWh/capita. The important question to be answer-

**Table 1.** Electric power density in Western European countries and in the United States (1968).

country	population x 1000	area km <sup>2</sup>	population density inhabitants /km <sup>2</sup>	total electricity consumption			total electricity production	
				GWh	kWh/ inhabitant	GWh/km <sup>2</sup>	GWh	GWhth/km <sup>2</sup>
Netherlands	12,750	33,500	380	31,500	2470	0.94	0.95	0.94
Belgium	9,619	30,500	320	23,000	2400	0.75	0.81	0.75
United Kingdom	55,391	244,000	227	215,000	3880	0.88	0.74	0.88
Germany	60,205	248,500	242	197,000	3270	0.79	0.69	0.79
Italy	53,211	303,800	175	102,000	1920	0.34	0.18	0.34
France	50,082	551,200	91	120,000	2400	0.22	0.12	0.22
E.E.C.	185,867	1,167,500	159	473,500	2550	0.41	0.30	0.41
U.S.A.	201,166	9,363,400	21	1,435,000	7140	0.15	0.13	0.15

ed is "Just how probable it is that this trend will continue in the years to come?"

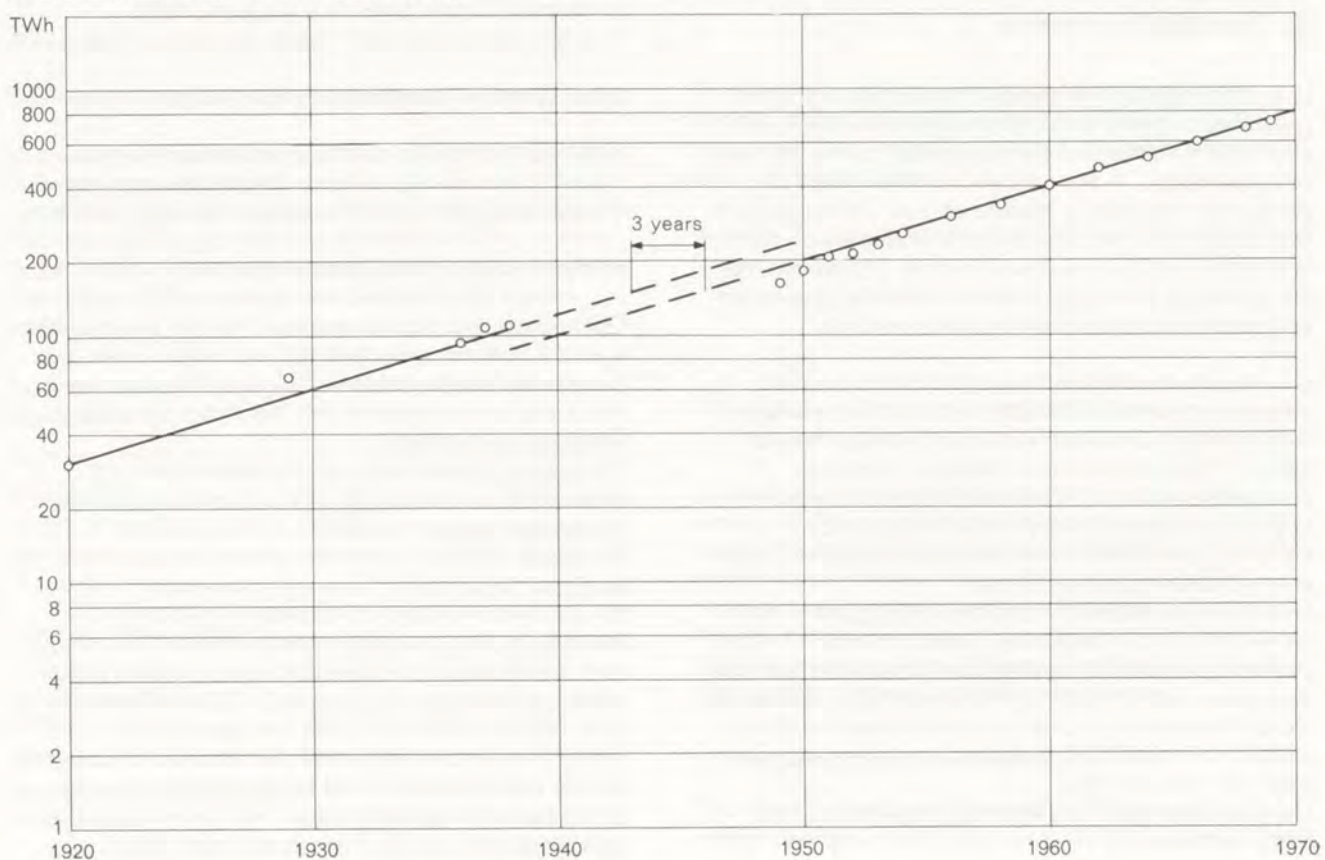
As the growth rate of the population is only about 1 % per year, the main trend of the growing electricity production is determined by a larger energy consumption in general, both in households and in industry, together with the strong tendency to "go" more electric.

If, however, new applications are found for electricity such as a switch over to electric cars and/or an increased use in domestic heating, new and larger

growth rates must be considered. There are good reasons to believe that, in the future, there will be a strong trend in this direction.

The first reason for this trend might be the fact that the use of electrical energy is a completely clean application of energy at the place where it is used, since the production of electricity which might cause environmental problems, can be realized outside heavily populated areas such as large cities. The second reason might be that nuclear energy production in place of fossil energy production would

**Figure 3** - Electrical energy consumption in the Netherlands during the period 1920-1970. The two lines indicate a doubling time of electricity production of ten years. (The shift between the two lines is equivalent to a delay of three years in the growth of production, caused by the second world war).



reduce air pollution considerably. Fossil fuel plants produce such large quantities of gaseous combustion products that it is impossible to concentrate them for storage. The tonnage of CO<sub>2</sub>, for example, produced in a fossil fuel plant is more than twice the tonnage of fuel burnt in the plant. In nuclear power plants air pollution can be avoided. As the direct applications of nuclear energy are restricted, the advantage of transforming nuclear energy into electrical energy is obvious.

The third reason is unlikely to play an important role in the next few decades but will undoubtedly be very important in the distant future. The fact is that the available fossil fuel reserves are diminishing so fast that a future without fossil fuel must be considered. The application of nuclear energy by burning uranium and thorium in breeder reactors can solve our energy needs, but again the transformation of nuclear energy into electrical energy seems to be the best way of supplying energy where it is needed.

As a general conclusion it seems reasonable to assume an average doubling time of 10 years in the Netherlands for the next three decades.

Working from these assumptions, an installed capacity of about 80,000 MW would be necessary in the Netherlands in the year 2000. The water surface needed for cooling the power stations would be about 800 km<sup>2</sup> (about 3% of the total land area) even without excessive heating of the water. The fresh water surface in the Netherlands is about 9% of the total land area. In addition two large estuaries and the North Sea coast are available for cooling purposes. Consequently, for this period of time a widespread use of cooling towers can be avoided.

## V. Transmission systems

In order to satisfy the demand, electricity has to be produced in power stations situated on well chosen sites and from there to be transported to the centres of consumption. In the next section the choice of production methods is discussed. For the transport of the electricity to the consumers a transmission system is required; and an additional system is required for the exchange of energy between different production systems for reasons of safety and economy.

Overhead transmission lines of 150 kV can have transport capacities of 1200–1500 MVA for a double circuit. With the modern extra high voltage lines of 380 kV (the highest level in Western Europe) a transport capacity of 4000–5000 MVA for a double circuit is possible. However, this indispensable electricity transport is very expensive compared with energy transport by gas or oil.

Overhead transmission lines are meeting more and more difficulties in populated areas or reserves. Consequently, a switch to underground transport would be desirable. However for 150 kV, present-day cables are about 5 times the price of overhead lines. For 380 kV cables — if technically feasible — the price increase might be 15 to 20-fold.

Therefore new developments are required, to find better solutions.

In the first place DC-cables should, in principle, be preferred over AC-cables, although the AC-DC-AC transformation would not be the only problem to be solved if they were used on a large scale.

Secondly, it is desirable to evaluate and develop cryogenic cables, either in a superconducting state or not. It seems improbable that such a development will be completed within the next decade.

To reduce the required transport capacity the building of peaktime units (e.g. gas turbines) in the neighbourhood of consumption centres is a likely development.

## VI. Production methods

The potential amount of water power available in the world, but as yet only partially used, is about equal to all the electrical capacity installed at present. Due to the fact that only Africa, South America and South East Asia still have large water power reserves available, these reserves cannot meet future electricity demands in the rest of the world.

The remaining modern production methods are all of a thermal nature. Expansion with thermal power stations, using either fossil or fissile fuels will therefore be the main activity in the years to come.

### A. Modern fossil fuel power stations

In the thermal power stations either a steam cycle (Rankine cycle) with a steam turbine, or a hot gas cycle (Brayton cycle) with a gas turbine is used to drive the electrical generator. The generator produces electrical energy in each case by rotating an electrical conductor (copper bars) in a magnetic field.

The theoretically possible thermodynamic efficiency of

these cycles is determined by the relation  $\frac{T_1 - T_2}{T_1}$ ,

deduced from the second law of thermodynamics.

$T_1$  and  $T_2$  are the highest and lowest temperatures of the steam or gas cycle. The actual efficiency is in fact,

owing to various losses, smaller than  $\frac{T_1 - T_2}{T_1}$ .

The highest practical temperature for the steam cycle is at the moment about 540 °C, and for the open gas cycle a few hundred degrees higher. These temperature limits are connected with the lack of good high temperature materials.

The lowest temperatures for the steam cycle are obtained in the condenser of the steam turbine and, for the gas cycle, in the outlet of the gas turbine. For the steam turbines condenser temperatures should not be higher than 30–35 °C, as any increase of 1 °C in the condenser means a decrease in efficiency of about 1/4%. For the once through gas turbines higher inlet temperatures are possible, and therefore higher outlet temperatures of a few 100 °C are still acceptable. Besides, due to the fact that gas turbines are mainly used as peaking units, the thermal efficiency is not the most important cost figure in their operation. As these power stations are so well known, it seems unnecessary to go into them in any more detail.



Figure 4 - First dutch nuclear power station at Dodewaard (Photo KLM Aerocarto N.V.).

### B. Present-day fissile (nuclear) power stations

In present-day light water nuclear reactors the steam temperature must not exceed 300–320 °C so as not to approach the critical temperature of water (374 °C). This results in lower thermal efficiencies (and, in turn, larger cooling water requirements) for nuclear than for conventional fossil fuel power stations with steam turbines.

Table 2. Thermal efficiencies and heat losses in different power plants

type of plant	thermal efficiency	heat outlet	
		to stack	to cooling water
fossil fuel steam turbine plant	38–40 %	10 %	50 %
fossil fuel gas turbine plant	22–25 %	75 %	no
light water reactor plant	30–32 %	no	70 %
advanced high temperature reactor plant	38–42 %	no	60 %

For advanced reactors with high temperature gas cooling, better efficiencies can be obtained. Furthermore, with helium cooling in sight, a closed turbine loop will be possible.

In Table 2 a few data concerning these efficiencies and losses are given.

## VII. Future electric power production

Consideration should also be given to other electric power producing methods which are under examination at the moment but still not available for practical applications. On the one hand there is fissile fuel, thorium or uranium, in breeder reactors; on the other hand fusion fuel — fusion of hydrogen — in thermonuclear reactors. Both of these, together with direct conversion methods, are evaluated below.

### A. Future nuclear power stations

The nuclear reactors discussed in VI.B are all convertor reactors, which are consuming the scanty cheap

reserves of uranium 235 at an alarming rate. By the end of the century scarcity of cheap natural uranium will increase nuclear fuel costs considerably. Therefore breeder reactors — whose main requirements are uranium 238 and thorium, which are both available in abundance — are essential for the large-scale long-term production of nuclear energy.

Without going into detail, two groups of breeder reactor should be considered.

### 1. Fast breeders with liquid sodium cooling

These reactors are being developed in many different countries (USA, UK, France, Germany-Belgium-Netherlands, USSR). It is not yet certain how much development time will be needed, nor is it known how acceptable this reactor will be, economically, as regards the effect of large fast neutron fluxes on the construction materials inside the reactor. Its thermal efficiency could be in the region of 40%. Other fast breeders, with gas cooling, are discussed.

### 2. Thermal breeders (USA — molten salt reactor, Netherlands — liquid suspension reactor).

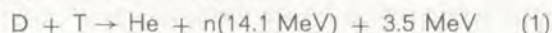
The fundamental material difficulties mentioned for the fast breeders are not so serious for thermal breeders, and, in addition the fissile inventories are much smaller. However, far less development effort is being applied to thermal breeders, so that the development time required will be at least as long as for fast breeders. The thermal efficiency of the suspension reactor will be about equal to the thermal efficiency of light water reactors (30%).

From a physical point of view both groups of reactors are possible. Just how economically acceptable they will be remains to be seen in the coming decades.

## B. Controlled thermonuclear reactions

Without a few remarks about fusion reactors this survey would be incomplete. The two fusion reactions that can be discussed are the deuterium-deuterium (D-D) and the deuterium-tritium (D-T) reactions. The first would be the preferred reaction due to the fact that for every 5000 hydrogen atoms, one heavy hydrogen (deuterium) atom is available in the world, which means an inexhaustible energy source comparable with thorium or uranium 238 in breeder reactors. However, it is possible that only the second reaction, between D and the very heavy hydrogen atom (T) (which does not exist in nature) will be attainable, due to the required plasma densities and temperatures.

In this reaction a helium atom, a fast neutron (14.1 MeV) and an additional amount of energy of 3.5 MeV are generated in the plasma.

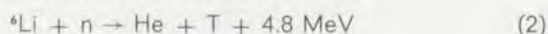


The high energy neutron leaves the hot plasma and transfers  $\frac{14.1}{14.1 + 3.5} = 0.8$  of the fusion energy to a

blanket.

The high temperature ( $> 100,000,000^\circ\text{C}$ ) and plasma stability problems, while not yet solved, are perhaps

not insuperable. The amount of deuterium in the world will be quite sufficient even beyond the foreseeable future; the problematical factor is the tritium, which does not exist in nature and therefore must be produced outside the D-T plasma by the high energy neutron from (1), with the reaction:



${}^6\text{Li}$  is one of the freely existing lithium isotopes.

Lithium in its natural state contains  $7\frac{1}{2}\%$   ${}^6\text{Li}$  and  $92\frac{1}{2}\%$   ${}^7\text{Li}$ .

In reaction (1) only one neutron is formed per fusion reaction. This neutron can produce a new T nucleus as long as it is not lost by leaking out of the reactor or by capture in structural materials. As these losses are larger than zero a certain excess amount of neutrons must be produced. This is possible with reaction (3), using beryllium:



Although a reasonable amount of lithium seems to be available in the world — sufficient at least to produce an amount of energy equivalent to the fossil fuel reserves — it is not at all certain that there will also be sufficient beryllium available for the necessary reaction (3).

For these reasons fusion reactors are a doubtful proposition, and anyhow not to be expected in this century.

## VIII. Direct conversion methods for electricity production

Apart from the Rankine and Brayton cycles a few other more direct conversion methods for electricity production can be mentioned.

### A. Magnetohydrodynamic (M.H.D.) generators

In modern thermal power stations, either conventional or nuclear, the electrical generator is, as mentioned before, a machine in which a solid conductor is moving in a magnetic field. However, there are other conductor materials, liquid or gaseous, which can also be used. Of the liquid conductors, a liquid metal such as molten sodium is a possibility.

However, more development work is being carried out on the gaseous conductors.

As a gaseous conductor can be used:

- A hot ionized gas ( $> 2000^\circ\text{C}$ ), often seeded with sodium or cesium. It can be blown through a magnetic field.
- An extremely hot, fully ionized, gas such as is present in a fusion reactor. For the temperatures required (about  $100,000,000^\circ\text{C}$ ) the electrical conductivity is far higher than in normal metals. This would therefore be, in theory, an extremely good medium for an M.H.D. generator.

M.H.D. generators using a) are being developed. However, such high temperatures are required that satisfactory structural materials both for the gas duct

and for the electrodes are not yet available. The simplest construction will be a once through system where, by burning fossil fuels, the very hot gases are blown through the M.H.D. installations. The gases at the outlet of the M.H.D. itself would still be hot enough to produce a certain amount of steam for a steam turbine plant. With this system efficiencies of 50 % could be obtained.

For a recirculation system where the gas (helium), after cooling in the M.H.D. generator, is recirculated through a nuclear reactor for re-heating, even more robust material properties are required. However, if the material problems were solved, an efficiency of about 70 % would be possible.

M.H.D. generators using b) would be of no practical value. In a fusion reactor using a D-T reaction (see preceding section) only 15 % of the energy produced remains in the hot plasma and is thus available for use in an M.H.D. generator. The other 85 % of the energy is transferred to a blanket surrounding a fusion reactor where temperatures must not be higher than 500–600 °C. Therefore at least 85 % of the total energy must be converted into electrical energy by conventional methods alone and only 15 % can, perhaps, be transformed with a high efficiency in the plasma itself using the M.H.D. method.

#### **B. Photoelectric generators and thermoelectric cells**

The energy of the sun intercepted by the earth is about 100,000 times greater than the electrical capacity installed in the world at the moment. However, transforming this energy by means of photoelectric cells seems to be completely impracticable. Even with a conversion efficiency of 10 % it would be necessary to cover a surface of 40 km<sup>2</sup> for a power station of 1000 MW. And even if this were acceptable, the storage of this energy in order to be able to use it at night would be impossible with methods known at present. The same objection applies to thermoelectric cells.

#### **C. Thermionic convertors**

Thermionic convertors are devices with a very hot electron-emitting cathode and a low temperature anode. Although the thermal efficiency can be reasonably high and the device has the advantage of having no moving parts, the very strict dimensional requirements of the gap between the diodes make a large scale application rather impracticable.

For very small power sources, such as in space vehicles, the methods mentioned in VIII.B and VIII.C can be of value. The devices mentioned in VIII.B are also widely used for measuring light intensities and temperature differences. For normal electric power production, however, none of these methods can be considered realistic.

#### **D. Direct conversion by fuel cells**

In electrochemical fuel cells chemical energy can be converted into electrical energy on catalytic surfaces. As the surface properties determine the efficient operation of these fuel cells very clean chemicals such

as hydrogen, or very pure hydrocarbons, are required so as not to poison the catalysts. Although small scale applications may be possible, larger scale applications are not foreseen.

### **IX. Additional remarks**

So far only the production of electricity has been discussed — with a brief look at its transmission. However, there are two cases where heat and electricity can sometimes be more advantageously produced simultaneously than separately. In industries with large low temperature steam requirements it is profitable to produce high temperature steam, using it for the production of electricity by a counter pressure turbine, and the remaining low pressure steam for other industrial purposes, such as in paper factories. In these cases the primary need is heat, but relatively cheap electricity can be obtained at the same time. Any further electrical energy required can be supplied from outside. The electricity production per unit heat input is of course much lower than in normal electric power station (about 12 %). In the Netherlands about 10 % of all electricity is produced in this way.

The second case is a "total energy system" where a balance is foreseen between electricity production on the one hand, and central heating or air conditioning on the other without an external supply of one of these energy forms. It seems to be difficult to find a sufficiently constant balance during the year. Even in the United States where the total energy system is strongly advocated, and where air conditioning during summertime is common practice, this type of power production remains a negligible percentage of the total electrical energy production of the country. Furthermore it should be realized that, by using a total energy system in a city, local pollution arising from local energy production from fossil fuels (nuclear reactors are too large in this context) is unavoidable.

### **X. Conclusions**

Summarizing this short introduction the following conclusions can be drawn:

1. The application of electrical energy is the application of completely clean energy.
2. The production of electrical energy is connected with the following environmental effects:
  - the heating up of cooling water, or the evaporation of water in cooling towers attached to fossil or fissile fuel plants.
  - the pollution of the air by combustion products from fossil fuel plants.

However, by placing electric power production units outside heavily populated areas, environmental effects can be better controlled than in the case of direct combustion of fossil fuel inside populated areas.

## CHAPTER 2. DISCHARGE OF WASTE HEAT

by K. J. Keller

### Summary

*In the next decades electric power will still have to be produced with steam powered turbines, implicating a need for cooling water.*

*Demands for cooling water can be met by once through fresh or salt water cooling, by surface cooling or by cooling towers.*

*The cooling water situation in Western Europe is briefly reviewed. The above-mentioned cooling methods and attendant problems are thoroughly discussed for the Netherlands.*

*Regarding future cooling water needs the available reserves in the Netherlands are estimated.*

*Some possible beneficial effects of heated cooling water discharge are mentioned.*

### I. Introduction

#### A. Electricity production with steam cycles implicating the use of cooling water

Nowadays electricity is mainly produced by steam cycles [7]. Generators are driven by steam powered turbines. For several reasons these steam turbines need condensers with some kind of cooling. These reasons are:

- Environmental. Large turbines need hundreds of tons of steam per hour. Discharging such large quantities of steam directly into the atmosphere would cause unacceptable environmental problems.
- Economic. Modern turbines need boiler feed-water of an extremely high purity. It would be very uneconomical to let this highly purified water escape into the atmosphere.
- Thermodynamic. The efficiency of the steam cycle is highly increased by application of a condenser. Steam freely discharged into the atmosphere has to do work against atmospheric pressure, which results in losses. The lower the temperature, the lower the pressure in the (vacuum) condenser and the higher the efficiency.

In the next paragraph a short review will be given of alternative methods for electricity production without steam cycle.

#### B. Alternative methods for electricity production requiring less or no cooling water.

1. *Hydroelectric power generation* is very attractive. Because neither fuel nor cooling water is needed, there is neither air pollution nor thermal pollution. Unfortunately hydroelectric power requires high investment, large height differences and is only of a very limited availability all over the world. Hydroelectric power, though it may be of great importance in some countries at this moment, will therefore play only a very limited role in the future.

2. *Aeolic power generation* never played a role of any importance. Though recently enormous windmills were planned in Siberia [1] where the "Bora" has a high and constant velocity, this way of power generation will be of even less importance than the previous one.
3. *Electric power generation by gas turbines* has a very low efficiency and is therefore restricted to special applications as for the generation of peak-power or in combination with other processes where heat is needed. The advantage (!) of the low efficiency is that cooling processes occur at a higher temperature, such that direct or indirect air-cooling can be used for the rather small units so far in operation. It is doubtful whether larger units could be also operated on air-cooling and even in combination with other processes such as desalination of water by flash evaporation more heat is finally converted to the cooling water than in steam cycle power generation. Although gas turbines might play some part in power generation in the future, the cooling water problem will not be much easier.
4. A number of *non-conventional ways of power generation* such as several methods of direct conversion (thermoelectric, thermionic, magnetohydrodynamic, fuel cells, etc.) are still in the development stage [7]. In the next two or three decades these methods cannot be expected to play a role of importance in practical power generation.

Thus it will be accepted in the discussion of cooling water problems, that electric power in the next two or three decades will have to be generated mainly in the conventional way with steam turbines with their inseparably connected cooling water needs.

#### C. Quantity of heat discharged by a power station

A modern fossil fueled power station discharges with the cooling water about 280 Mcal/s for a generated

power of 1000 MW. Thus assuming, for instance, a temperature rise of 7 °C, 40 m<sup>3</sup>/s of cooling water is needed. Present-day nuclear power stations discharge about 50 % more heat with their cooling water, but in the future their efficiency might be expected to increase.

In the following a cooling water need of 50 m<sup>3</sup>/s will be assumed for 1000 MW of generated power, so a certain percentage of nuclear power stations is included, which percentage may rise with rising efficiency of these nuclear stations.

#### D. Alternate methods of cooling

1. "Once through" fresh water cooling. If there is a sufficient supply of fresh cooling water from a lake or a large river and this water may be discharged after heating in the condenser in such a way that it can never reach the intake again, for instance by discharging it into another river or lake, the cooling is (or seems to be) very simple.
2. Once through salt water cooling. Taking in water from the sea or the ocean and discharging it at a suitable point may give also a simple once through cooling with some additional problems (corrosion, mussels) which don't occur with fresh water.

Looking into a larger environment however shows, that this "once through" cooling only applies for one single power station. As soon as there are more power stations on the same river, lake or seacoast, one has to make too with the next type of cooling:

3. Surface cooling. In surface cooling, water is taken from a small lake (may be natural or artificial) and after heating in the condensers of a power station is discharged to the same lake at a remote point, such that it may be used again for cooling after it has had the opportunity to cool down by transfer of heat from the water to the atmosphere at the interface. As mentioned before: in the final stage "once through" cooling must be also surface cooling.
4. Cooling towers. In regions where there is an insufficient supply of fresh or salt water and where there are no natural or artificial cooling lakes available, cooling towers can be used. These cooling towers can be of the wet type, in which the heated water is cooled down in direct contact with the atmospheric air, mainly by evaporation; or of the dry type where the water is passed through large radiators in which the heat is transferred to the air without evaporation losses. In both types the air may have natural draught or forced draught.
5. Combinations of the aforementioned cooling methods. At a particular site some of the aforementioned cooling methods may be possible but none sufficient for the whole power station. In such a case a combination of two or three cooling methods can be used.

#### E. Economic evaluation of alternative cooling methods

The economic evaluation of the alternative cooling

methods is very difficult as it depends on many factors that may vary widely from country to country and even from site to site in the same country. Some of the relevant factors are the availability and the price of the fuel (a power station on a coal mine or a nuclear power station in a desert) and the high transportation costs of the generated electricity to the place where it is needed.

Although not applicable to Europe, the results of an evaluation for America given by Hauser [2] will be mentioned here as the results are presented in a very illustrative manner. Hauser calculates the effect of all parameters on the additional cost of a kWh using fresh water cooling as a base. He converts this figure to the distance that the plant with the alternative cooling could be located from the load centre assuming an adequate supply of fresh cooling water. Hauser's results are given in Table 1.

Table 1.

Cooling type	Equivalent transmission distance in miles
fresh water	Base
cooling ponds	34.3
sea coast	13.2
wet cooling towers, mechanical draft	82.5
wet cooling towers, natural draft	78.2
dry cooling towers	321.6

These figures may depend largely on the circumstances, such as ground prices for cooling ponds, etc. However the result that wet cooling tower costs are corresponding to an equivalent distance of about 80 miles and dry towers about 300 miles gives a fair idea of the relative costs. With the same restrictions as for the evaluation of Hauser, it may be said that wet cooling towers cause an increase of 5-10 % and dry cooling towers of 10-15 % in the kWh price.

## II. The cooling water situation in Western Europe

Most European countries estimate that their electricity requirements for the year 2000 will be several 100,000 MW, whereas the cooling capacity of most European rivers could better be expressed in units of 10,000 MW. It is thus clear that the rivers will be insufficient to meet the cooling water needs of the total power production in the future.

For countries as for instance Italy, Great Britain and Denmark, where most vital parts have no larger distances than 100 or 200 km from the seacoast it may be expected from paragraph I.E that in the future many power stations will be situated at the seacoast, unless other circumstances impede this development as for instance in the Netherlands (section IV).

For less favourable situated countries as France and Germany where many vital parts of the country are more than 100 or 200 km from the coast, the cooling



water reserves of the rivers as well as those of the lakes must be exploited as intensively as possible. Further power stations will depend on cooling towers.

Although it seems unlikely before the end of this century a possible change in the situation might be caused by the development of cryogenic cables. Such cables, whether superconducting or not, could make long distance electricity transport cheaper. As soon as this long distance transport is possible the electric power for regions without enough cooling water might be generated in regions with more cooling water, e.g. coastal regions.

After this short review of the general situation of the cooling water needs and reserves in Europe, the various cooling methods, their problems, the study of these problems and their importance for power production will be more thoroughly discussed for the Netherlands.

### III. Once through fresh water cooling on rivers

#### A. General

At first sight the once through cooling water problems on a large river as the Rhine or Waal seem to be very simple. The cooling capacity of the river at a certain point can be easily calculated from the flow of the river  $Q$  m<sup>3</sup>/s and the allowed increase in temperature ( $\Delta T$  °C) of the water.

For a Rhine flow of 1000 m<sup>3</sup>/s (mean value 2300 m<sup>3</sup>/s) a summer temperature of 24 °C and a temperature of 30 °C at the cooling water outlet, the cooling capacity of the Rhine would be  $Q \cdot \Delta T = 6000$  Mcal/s. According to paragraph I.C this cooling capacity would be sufficient for conventional power stations of more than 20,000 MW.

However there are many problems involved in effectuating this cooling capacity. All these problems are studied in close cooperation by Rijkswaterstaat <sup>1)</sup>, RIZA <sup>2)</sup>, the involved power stations and KEMA <sup>3)</sup>. A short survey of the problems is given in the paragraphs III. B to III. F.

#### B. Recirculation

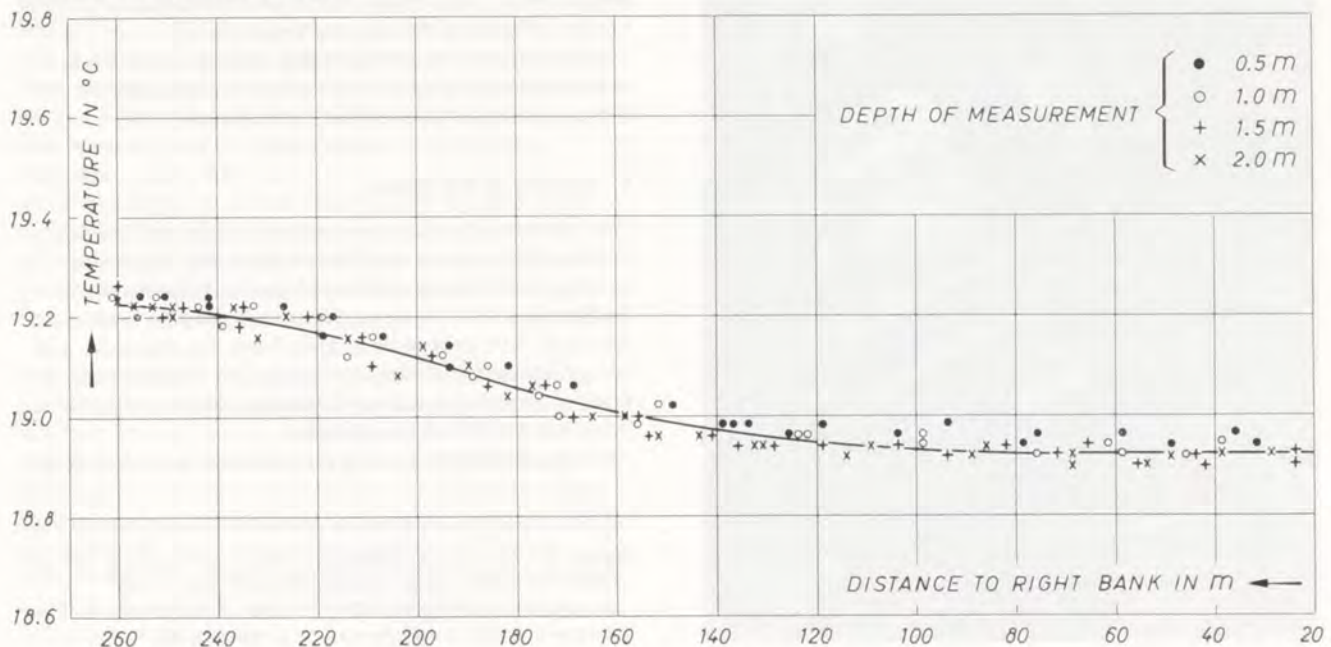
The building of one large power station of 20,000 MW on the Rhine would require that the total flow of the river be passed through the condensers. The many problems related to such a project, which could only be solved by building a dam across the Rhine with locks for shipping, will not be discussed here. For power stations of 2000 to 3000 MW about 100–150 m<sup>3</sup>/s of the river flow has to be used for condenser cooling. Model measurements by the "Waterloopkundig Laboratorium" (Hydraulics Laboratory) showed that, even in the case where in- and outflow are very close to each other, recirculation will be no problem for such power stations on the Rhine and Waal. However in other rivers with a lower velocity this recirculation may spoil the "once through" cooling, with part of the heated water passing again through the condensers.

#### C. Cross currents hampering navigation

The utmost care should be taken to prevent hindrance to shipping by cross currents near in- and outlet. The solution of this problem may depend on the local conditions, but is expected to be attainable in most cases.

<sup>1)</sup> Government Service for Public Works and Water Control.  
<sup>2)</sup> Government Institute for Sewage Purification and Industrial Waste Treatment.  
<sup>3)</sup> Joint Laboratories of the Electric Utilities in the Netherlands.

Figure 1. Temperature distribution across the river Waal, about 12 km below the cooling water discharge point of the electric power station at Nijmegen.





#### D. Sand transport problems

There is a considerable sand transport over the bottom of the Rhine and Waal. Disturbances in the flow pattern may cause changes in sand transport leading to shoals in the river that are unacceptable for shipping. Studies on this very difficult problem are still in progress but seem to show that sand deposition will be a bottleneck for large power stations (3000 MW or more) on the Rhine and Waal. A possible solution might be the displacement of deposited sand by suction dredging.

As these problems demand urgent solution, simultaneous investigations are being made on the recirculation for a power station with its cooling water inlet downstream of the cooling water outlet. These studies are made both in a model and near the existing power station at Nijmegen. Although sand problems are expected to be much smaller and the recirculation is expected to be, from preliminary results, not more than 30 % (for a cooling water flow of about 10 % of the total river flow), this recirculation however will certainly aggravate the problems mentioned in paragraph III. F below.

#### E. Mixing of the discharged cooling water with the river

The mixing of the discharged cooling water with the river has been studied by means of temperature measurements near the power station at Nijmegen on the Waal and near the power station at Harculo on the IJssel. The mixing process proceeds very slowly: on the Waal the heated region only reached the centre line of the river at a distance of about 16 km below the point of discharge. The mixing process could roughly be described by turbulent mixing with a horizontal diffusion coefficient of the order of  $0.2 \text{ m}^2/\text{s}$ . Figure 1 gives the temperature distribution across the Waal at a distance of about 12 km below the point of discharge from the power station at Nijmegen. A good illustration of the cooling water discharge and its gradual mixing with the river is given in Figure 2, an infra-red photograph of the power station at Harculo on the IJssel, made by the "Nationaal Lucht- en Ruimtevaart Laboratorium" (National Aerospace Laboratory). The investigations of the mixing process show that it is advisable to locate power stations alternatively on the right and on the left bank of the river.

#### F. Heating of the Rhine

One of the most severe problems facing the Netherlands in their future use of the Rhine for condenser cooling is the large number of power stations that Switzerland, Germany and France intend to build on the river. The problems arising from this common use of the Rhine for cooling purposes are discussed in a special working group on "Thermal Pollution" of the International Rhine Commission.

The consequences for the Netherlands will be that the

**Figure 2.** Infra-red photograph of the electric power station at Harculo on the IJssel showing the diffusion of the discharged cooling water with the river. Photography by the "Nationaal Lucht- en Ruimtevaart Laboratorium".

Rhine will arrive at a higher temperature than the natural maximum summer temperature of 24 °C mentioned in paragraph III. A. The result is that not only the theoretical cooling capacity decreases, but due to the maximum value of the cooling water outlet temperature of 30 °C allowed by the Netherlands authorities, the increased summer temperature also poses a limit to the possible temperature rise in the condensers. The consequence would be larger and more expensive condensers, and the cooling water flow must also be increased and this is limited by the sand transport problems discussed in paragraph III. C. Thus an increase of the maximum summer temperature of the Rhine with only one or two degrees centigrade will cause severe difficulties for the use of the Rhine for cooling purposes in the Netherlands.

The surface cooling (to be discussed in section V) for a river like the Rhine gives only very slight relief for the Dutch power stations: at a flow of 1000 m<sup>3</sup>/s only 1/4 of the temperature rise is cooled down over a distance of 100 km, a very long distance in a small country like the Netherlands!

The only way to use the Rhine for cooling purposes in the Netherlands in spite of an increased temperature at the Dutch-German border would be to build a weir across the river near Varik with locks for shipping. By raising the water level with this weir the forelands would be flooded, the cooling surface would be increased and the water temperature would drop sufficiently to allow thermal power stations of considerable capacity to be installed near the weir. The high costs and the delay for shipping make the adoption of this solution rather improbable despite the advantage of increased cooling capacity.

#### IV. Once through cooling with seawater

Seawater cooling presents technical problems which can be solved at the expense of extra costs, but the essential difficulty is making it a real "once through" cooling. In the Netherlands there are only a few places where this is possible without prohibitive civil construction costs. One of these locations is near Rotterdam on the "Maasvlakte", where a larger power station will be constructed. Model studies have shown that recirculation of heated water to the inlet is negligible at this site.

At other locations on the Dutch coast the sea is not accessible for cooling water purposes due to the dunes and the beaches. In addition enormous sand transport along the coast would make the constructions required to prevent recirculation very expensive.

The best method of using the North Sea for cooling purposes would be by locating power stations on the Wadden islands or on artificial islands. The latter might be a good solution in the far future if these artificial islands have also harbour facilities for large tankers and space for industry causing environmental problems. At the moment the costs would be prohibitive and the electricity transport from the islands, artificial or natural, would be beyond the present technical possibilities.

Another possibility to use seawater cooling lies in the estuaries of the Scheldt and the Ems, but this is not a real "once through" cooling. Intensive tide movements in these estuaries cause the discharged water to pass along the inlet making some recirculation unavoidable. However by careful siting of the inlet and the outlet, mixing with the estuary may be so intense that the increase of the inlet temperature is acceptably small. Moreover stratification may be used to avoid recirculation. On both estuaries the construction of large power stations has started.

#### V. Surface cooling

As mentioned before the "once through" cooling systems are, in the final stage, also dependent on surface cooling. This fact together with the use of smaller and larger lakes and other nearly stagnant waters for cooling purposes make a proper understanding of surface cooling effects very essential. This particularly applies to the Netherlands, where considerable water surfaces are available while the running water of the Rhine and the seawater can only provide a fraction of the cooling capacity for the total power needs until the year 2000.

The potential use of stagnant waters for surface cooling depends on the heat exchange processes at the water-air interface. These processes are many: incidental gross (short wave) solar radiation, reflected gross solar radiation, incidental (long wave) atmospheric radiation, reflected atmospheric radiation, long wave back radiation and heat losses due to evaporation and convection.

Moreover all these processes vary with the time of the day and throughout the year. Many investigators have tried to calculate the heat exchange coefficient due to these processes [3, 4, 5], but their conclusions show considerable differences.

Direct measurements of the heat exchange coefficient in a cooling water circuit would be necessary to decide between the various theoretical results. However for a number of reasons direct measurement is very difficult:

- a) most present power stations are rather small compared to the cooling capacity of the water surfaces used for their cooling
- b) the heat exchange coefficient is so small, that a vertical water column of 1 m<sup>2</sup> horizontal cross section loses only about 10<sup>-5</sup> Mcal/m<sup>2</sup>.s.°C.

The latter heat loss rate is equal to the exchange in one second of a surface layer of only 10 μm thick against a layer of the same thickness and one degree lower temperature. In other words: an exchange through the vertical walls of the water column of only 36 liters per hour with 1 °C temperature difference. This clearly demonstrates the difficulty of direct measurements: a carefully chosen part of a cooling circuit must be used for the experiments where no exchange with the environmental waters is possible or, if unavoidable, only to an accurately known extent.

Several experiments have been made by KEMA on this subject and the first results of the most promising experiments are expected in the near future. Preliminary results show no evidence that the results will differ much from the value of  $10^{-5}$  Mcal/m<sup>2</sup>.s.°C for the heat exchange coefficient determined in a very elegant manner by *Wemelsfelder* [6]. *Wemelsfelder* used routine temperature measurements of Rijkswaterstaat to determine the heat exchange coefficient by observing the velocity with which the water temperature follows sudden changes in air temperature. With the known value of the heat exchange coefficient  $A$  the surface cooling capacity can be calculated. A quantity of  $Q$  m<sup>3</sup>/s of water discharged with a temperature increase  $\theta$  (o) above the natural temperature will cool down to a temperature increase  $\theta$  (F) above natural temperature by passing through a stretch of water with a surface of  $F$  m<sup>2</sup> according to the formula:

$$\theta (F) = \theta (o) e^{-\frac{AF}{Q}}$$

Sometimes a very rough figure is used for convenience: the surface cooling capacity of a cooling circuit should be one MW per ha (1 ha = 10<sup>4</sup> m<sup>2</sup>). This figure depends on many factors and can be used as a thumb-rule, but the accurate cooling capacity should be calculated from the formula.

## VI. Cooling towers

Where natural cooling capacity on surface waters is insufficient, cooling towers can be used, be it at the expense of higher electricity costs. The use of cooling towers in the Netherlands has, however, a number of disadvantages that follow from the fact that the country has very high densities of: population, network of roads, built-up areas, waterways and harbours, electricity consumption [7], industries and nature reserves.

These facts make the use of cooling towers unattractive for the Netherlands and their use on a large scale nearly impossible.

Cooling towers of a capacity for about 500 MW are large buildings, with a diameter of about 100 m and a height of more than 100 m. Thus the use of some six cooling towers for a power station of 3000 MW would greatly extend the area of the site, not a welcome proposition in a country where space is at a premium. The high buildings will hardly be accepted on the grounds of necessity; the flat countryside makes them visible from a long distance.

The use of forced draught cooling towers leads to somewhat lower buildings for the same capacity, or greater capacity for the same height, but noise from the ventilators may cause other problems in many areas of the country.

Perhaps the most serious problem for the Netherlands might be the long cooling tower plumes which may occur under certain meteorological conditions. This problem has been studied theoretically by the

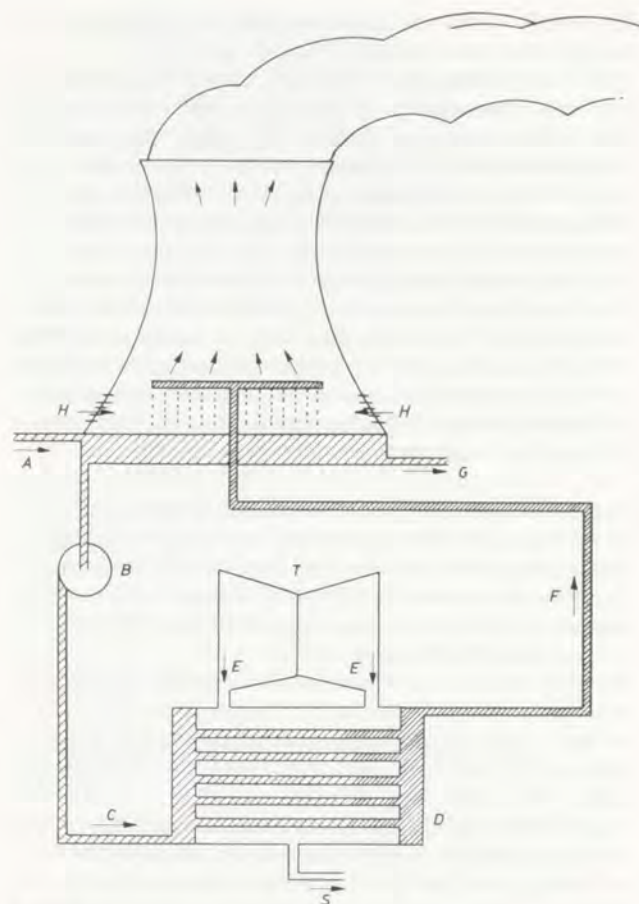


Figure 3. Diagram of steam turbine with condenser and natural draught cooling tower

- A = cooling water supply
- B = cooling water pump
- C = cold water flow to condenser
- D = condenser
- E = steam flow to condenser
- F = hot water flow to cooling tower
- G = discharge
- H = air inlet
- S = condensed steam
- T = turbine

KNMI<sup>4)</sup> [8] who estimate that in certain circumstances the plume length could be several kilometers. The theoretical results should be verified experimentally, but it is clear that these plumes are undesirable in a country with a high density of built-up areas and of traffic on the roads and waterways.

Dry cooling towers produce no plumes but the other problems are more severe due to larger size and considerably higher costs (cf. paragraph I.E).

The difficulties attendant on the use of cooling towers in the Netherlands make it important to use the natural cooling reserves as far as possible. In special cases however, where the natural cooling capacity is not sufficient, some additional cooling towers may be used.

<sup>4)</sup> Royal Netherlands' Meteorological Institute.

## VII. Cooling water reserves in the Netherlands

Future electricity demand in the Netherlands is discussed by Bakker and Went [7] and estimated at 80,000 MW for the year 2000. There seems to be enough surface water potentially available for cooling the power stations that will generate this power. The cooling water needs of industry are only a fraction of those for electric power stations, this fraction being of the same order of magnitude as the uncertainty in the estimated power needs (about 15 %). Unless the industrial needs would rise much faster than those of electric power stations, sufficient cooling capacity for industries will be available.

A rough estimate of the cooling capacity that might be available without violating biological limits is given in Table 2.

**Table 2.** A rough estimate of the cooling capacity that might be available in the Netherlands without violating biological limits.

Cooling Towers	10,000 MW
Rhine and Waal	20,000 MW <sup>1)</sup>
IJssel lake	25,000 MW <sup>2)</sup>
Delta lakes	25,000 MW <sup>2)</sup>
Natural and artificial lakes	10,000 MW
Surface cooling along IJssel and Maas	10,000 MW
Surface cooling lower rivers	10,000 MW
Estuaries	15,000 MW
North Sea (accessible locations)	10,000 MW
Total	135,000 MW
Wadden Islands and North Sea artificial islands	possible reserve

<sup>1)</sup> as mentioned in paragraph III. F heating of the Rhine in other countries would reduce this figure

<sup>2)</sup> with an increase of the mean surface temperature of less than 1 °C.

The cooling reserves given in this table seem to be amply sufficient for the power needs of the year 2000. But though the estimate of the potentially available cooling capacity was made rather conservative, there may be other reasons that may hamper the effectuation of the estimated cooling reserves. It might, for instance, be difficult to find good sites for power stations near the cooling water reserves. The most favourable sites for power stations might also be claimed for industry, traffic (harbours, ways, airfields) or recreation.

It will be very important to try to effectuate the available cooling water reserves with the utmost care. It is therefore necessary that planologists take into account the necessity of building enough power stations on locations near the cooling water reserves and not too far away from the consumers to minimize environmental problems with high voltage lines. As an example of the increasing interest in cooling water problems on behalf of "Rijkswaterstaat" Wemelsfelder's paper [6] may be mentioned, in

addition to studies by various committees, comprising representatives from Rijkswaterstaat, RIZA, electric utilities and KEMA.

## VIII. Discharge of chemical substances by electric power stations

For the prevention of biological fouling of the condenser tubes chemical substances are sometimes added to the cooling water, continuously or intermittently. Generally the concentration of these substances does not cause problems. Moreover, the so-called *Taprogge* procedure for cleaning condenser pipes by means of small spheres of foam rubber or plastic may replace the chemical method in the future. For the suppression of mussel fouling with seawater cooling permanent chlorination with 0.5–1.0 ppm is sufficient [9].

## IX. Beneficial thermal effects

The thermal effects of cooling water discharges [10, 11] may be detrimental or beneficial. In papers on environmental problems there is an inclination to mention only the more or less detrimental effects that might occur when biological limits are surpassed. In this section some attention will be paid to possible beneficial effects.

Thermal discharges may keep waters ice-free during at least a part of the winter. This offers advantages for shipping and runoff of rivers and is biologically important for water-birds and, because the aeration of the waters is impossible under an ice-cover, it is also important for fish.

The increase of water temperature by thermal discharges may prolong the period during which phenols are decomposed.

Even the accelerated decomposition of all organic wastes may be an advantage as long as the oxygen content is sufficient, but too much waste and too high temperatures lead to the most serious detrimental effects due to oxygen deficiency. In some cases it may be advantageous to aerate the discharged cooling water to improve the oxygen content.

The cooling water discharges may be used in fish farms and for the accelerated growth of shrimps and lobsters.

The use of cooling water for agricultural applications has also been considered.

Those applications that would be not only beneficial by the accelerated growth of some product, but that would also eliminate the thermal effect problems, would be the most interesting, but unfortunately these applications are not very promising at the moment. The combination of electricity generation with water desalting by flash evaporation causes more dis-

charged heat than the generation of electricity alone. It is true that fresh water is gained, but the thermal problems are increased.

The use of the discharged heat of electric power stations for evaporation and thus for concentration of sewage has been suggested. By these methods two problems might be solved at one time, but it is to be feared that the technical problems for this procedure will be so difficult that evaporation of sewage by direct heating with gas or electricity would be much easier. The same might be true for the sometimes suggested use of cooling water for the heating of buildings or for irrigation of agricultural fields with warm water: the availability of and the demand for heat don't coincide, and the transportation of low-grade heated water is expensive.

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# CHAPTER 3. AIR POLLUTION FROM COMBUSTION PRODUCTS

by A. J. Elshout and H. van Duuren

## Summary

The combustion of fossil fuels in power plants produces emission of sulphur oxides, nitrogen oxides, ash particles, carbon, unburned (partially oxidized) organic materials and anorganic trace gases. An evaluation of these air pollutants, their concentrations and their properties, is given. Present and future emissions and their relationship to the fuel pattern are discussed. Methods of controlling emissions are reviewed. Attention is given to the control of ground level concentrations of air pollutants. In this connection stack height, plume rise and meteorological factors are discussed. Finally research and development contributing to a better understanding and control of emission and dispersion of pollutants in the atmosphere are considered.

## I. Combustion products

### A. Introduction

Combustible materials containing carbon and hydrogen have, for centuries, furnished man with his most versatile source of heat and convertible energy. In recent years he has, to a large extent, been weaned from the conventional solid fuels to the more convenient liquid and gaseous hydrocarbons.

Although nuclear power is likely to occupy an increasingly prominent position in the coming decennia, hydrocarbons will certainly continue to provide a significant portion of power supply.

When fossil fuels are burned chemical oxidation occurs, the combustible elements of the fuel being converted into gaseous products, and the non-combustible elements into ash. The gases resulting from combustion contain chiefly nitrogen, water vapour, carbon dioxide and oxygen — all of which are already present in the atmosphere — in addition to certain air contaminants.

Table 1 gives combustion data for some typical fuels, and shows how the composition of the flue gases varies with the C/H ratio of the fuel.

The air contaminants produced by fuel combustion can be divided into five categories:

1. Sulphur oxides
2. Nitrogen oxides
3. Ash particles
4. Unburned carbon, and unburned, partially oxidized, organic materials
5. Anorganic trace gases, such as hydrogen fluoride (HF) and hydrogen chloride (HCl).

### B. Sulphur oxides

The sulphur oxides are directly related to the composition of the fuel used. The sulphur content of coal and oil ranges from less than 1%, to 5% and more (by weight) — depending on the origin of the fuel —

most of this sulphur being converted into sulphur dioxide (SO<sub>2</sub>) on combustion.

The amount of sulphur emitted as SO<sub>2</sub> from coal combustion in pulverized coal-fired units is approximately 95%, with 1–2% of the sulphur being converted into SO<sub>3</sub>. The SO<sub>2</sub> emitted in the flue gas from fuel oil combustion is approximately 98% of the sulphur in the oil, a further 1–2% being emitted as SO<sub>3</sub>. A typical residual fuel oil, as shown in Table 1, yields a concentration of approximately 1000 ppm SO<sub>2</sub> when burned with the theoretical combustion air requirement. This concentration is equivalent to about 900 ppm SO<sub>2</sub> at 20% excess combustion air.

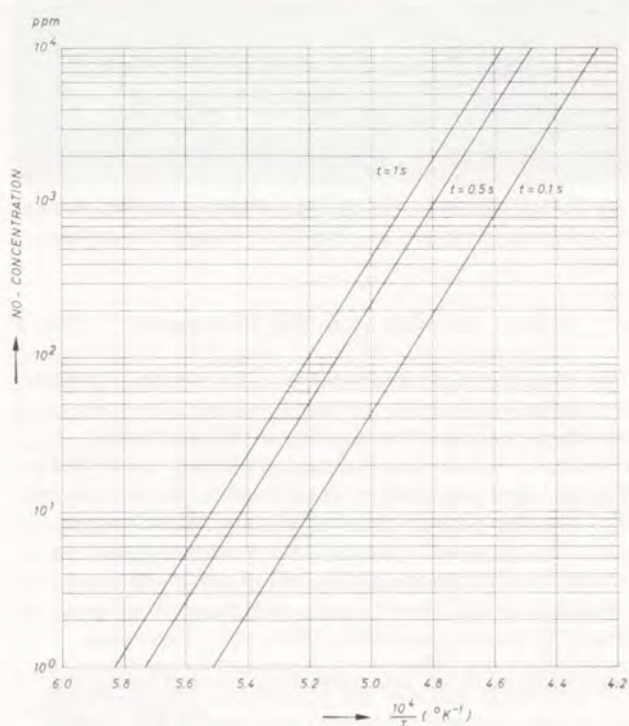


Figure 1 - Theoretical formation of nitric oxide (NO) in air, versus temperature and reaction time.

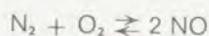


**Table 1.** Summary of combustion data for various fuels.

analysis	coal		oil		natural gas (Slochteren)				
	component	% (by weight)	component	% (by weight)	component	% (by volume)			
	C	74.0	C	86.10	CH <sub>4</sub>	81.30			
	H	4.6	H	11.78	C <sub>2</sub> H <sub>6</sub>	2.85			
	O	9.0	N	0.37	C <sub>3</sub> H <sub>8</sub>	0.37			
	N	1.0	S	1.72	C <sub>4</sub> H <sub>10</sub>	0.23			
	S	1.0	ash	0.03	O <sub>2</sub>	0.01			
	H <sub>2</sub> O	3.8			N <sub>2</sub>	14.35			
	ash	6.6			CO <sub>2</sub>	0.89			
gross heating value	7000 kcal/kg		10520 kcal/kg		8400 kcal/m <sup>3</sup>				
theor. combustion air requirement	7.54 m <sup>3</sup> /kg		10.85 m <sup>3</sup> /kg		8.41 m <sup>3</sup> /m <sup>3</sup>				
combustion products	component	% (by volume)		component	% (by volume)		component	% (by volume)	
		theor.	20 % excess air		theor.	20 % excess air		theor.	20 % excess air
	N <sub>2</sub>	75.35	75.93	N <sub>2</sub>	74.48	75.33	N <sub>2</sub>	72.00	73.07
	CO <sub>2</sub>	17.46	14.67	CO <sub>2</sub>	13.96	11.77	CO <sub>2</sub>	9.55	8.11
	H <sub>2</sub> O	7.10	5.96	H <sub>2</sub> O	11.46	9.47	H <sub>2</sub> O	18.45	15.65
	O <sub>2</sub>		3.36	O <sub>2</sub>		3.34	O <sub>2</sub>		3.17
	SO <sub>2</sub>	0.09	0.08	SO <sub>2</sub>	0.10	0.09			
amount of flue gases		theor.	20 % excess air	theor.	20 % excess air	theor.	20 % excess air		
per kg of fuel		7.91	9.42		11.51	13.68			
per m <sup>3</sup> of fuel							9.43	11.11	
per Gcal		1130	1345		1095	1300	1120	1320	

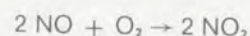
### C. Nitrogen oxides

In every combustion process the high temperatures at the burner result in the fixation of some oxides, due to oxygen and nitrogen combining to form nitric oxide (NO):



The equilibrium concentrations of the overall reaction are never achieved at the temperatures occurring in the furnaces. Thus the quantity of NO emitted is kinetically rather than thermodynamically controlled. Figure 1 gives an idea of the influence of temperature and reaction time on the formation of NO. Over the past decade various surveys have revealed that the emission of nitrogen oxides, NO in particular, from combustion equipment stacks can range from less than 100 ppm to more than 1500 ppm. These concentrations are affected by maximum temperature, by the load factor of the equipment, by the amount of oxygen (excess air factor), by furnace and burner design, by the rate of cooling of the combustion gases, and by the type of fuel burned.

In boiler practice most of the nitrogen oxides are emitted as nitric oxide. This NO can be oxidized in the atmosphere as a result of the reaction



Nitrogen dioxide (NO<sub>2</sub>) is the most toxic of the oxides of nitrogen and is an important component of the chemicals in photochemical smog. For these reasons it is usually assumed that all the emitted nitrogen oxides (NO<sub>x</sub>) consist of NO<sub>2</sub>.

In contrast to the emission of SO<sub>2</sub>, where the total amount released from any given equipment increases proportionally with the amount of fuel fired, the nitrogen oxide emission shows a graduated increase, as seen in Figure 2.

Most surveys in recent years have shown that nitrogen oxide emission rates vary from fuel to fuel, with coal-fired units producing the highest emission and gas-fired units the lowest. A survey in Los Angeles [1] for example, gave the following median values for the emission of nitrogen oxides: coal 1.3 kg/Gcal; oil 1.1 kg/Gcal; natural gas 0.8 kg/Gcal.

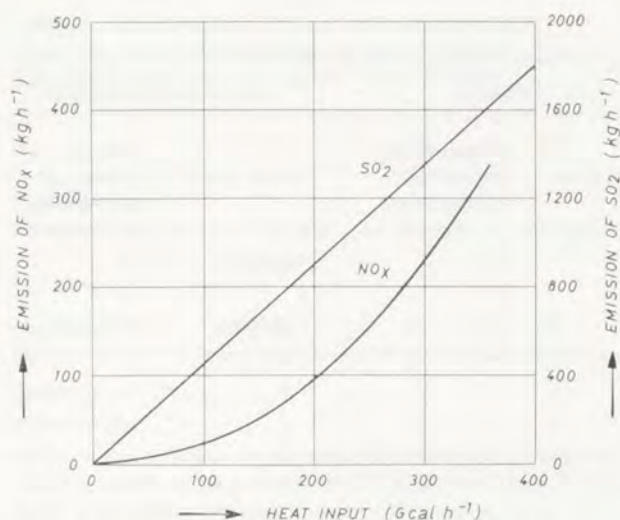


Figure 2 - Emission of sulphur dioxides and oxides of nitrogen from a 180 MW oil-fired power station (oil with 2.2 % S).

A survey made in the Netherlands in 1968, covering 13 power generating units, found an upper limit of nitrogen oxide emission for coal-, oil-, and gas-fired units of 3.0, 1.5, and 0.75 kg/Gcal, respectively [2].

One of the frustrating things about these nitrogen oxide emission rates is that they result from equipment designed and operated in accordance with the most efficient and up to date boiler practice. Some newer gas-fired power generating units in the Netherlands showed rather higher emission values, which should be attributed to the development of higher combustion efficiency.

This also explains differing emissions from combustion units of different sizes. For example, the median values given for nitrogen oxide emission by oil-fired combustion units used in power stations, industrial and domestic heating units are 1000, 750, and 125 g/Gcal respectively.

#### D. Ash particles

Particulate emissions from coal-fired units consist primarily of carbon, silica, alumina and iron oxide in the fly ash. The ashforming mineral matter in coal can range from approximately 4 % to 20 % (by weight), the constituent ratios being: SiO<sub>2</sub> 20-60 %; Al<sub>2</sub>O<sub>3</sub> 10-35 % and Fe<sub>2</sub>O<sub>3</sub> 5-35 %; the remainder being made up of CaO, MgO, Na<sub>2</sub>O, K<sub>2</sub>O and SO<sub>3</sub>.

A typical particulate emission factor for pulverized coal combustion without control equipment would be

Table 2. Particle size fractions for a typical pulverized-coal fly ash.

Fraction in $\mu\text{m}$	weight percentage
> 5	15
5-10	17
10-20	20
20-45	23
< 45	25

80 % of ash in the coal, with a particle size distribution in microns as given in Table 2. The values given in this table represent the load reaching the control equipment which is invariably used on this type of furnace. It is the efficiency of this equipment which determines the real emission.

The shape of the particles often gives an indication of the type of firing unit used, along with its combustion efficiency. Pulverized coal units generally produce small particles, which are glassy and spherical (Figure 3), whilst other stokers and domestic units produce larger particles, which are flakier and agglomerated.

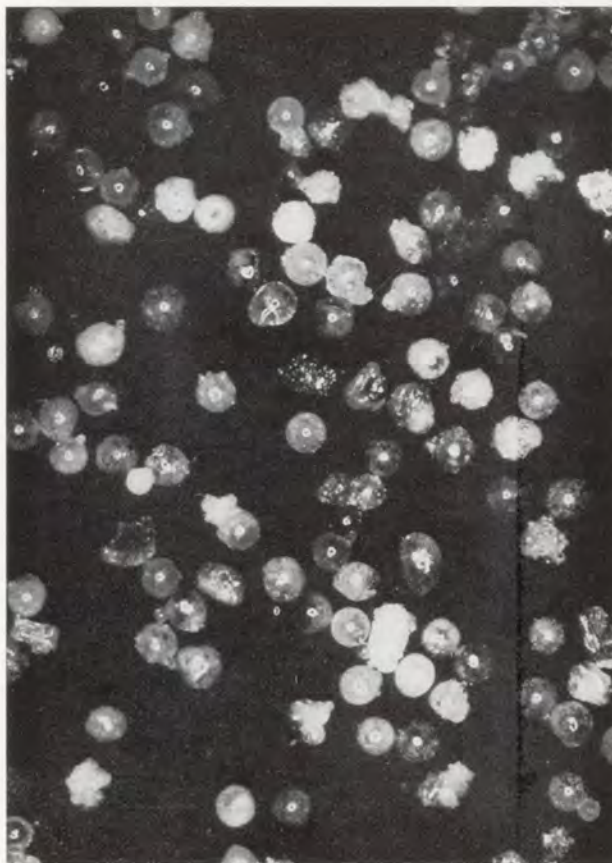


Figure 3 - Fly-ash particles from a 120 MW pulverized coal-fired unit (magnification 75x).

Particles emitted from fuel oil combustion consist in general of 10-30 % ash, 17-25 % sulphates, and 25-50 % carbon "cenospheres", formed during combustion. The particle size distribution is variable, ranging from less than 1 micron to 40 microns, but for the most part remains under 5 microns.

The normal range of emission rates is 100-200 mg/m<sup>3</sup>. No general statement can be made on the highly variable composition of the fly ash. The most frequently occurring constituents are Na, V, Ni, followed by Fe, Al, Ca and Mg.

#### E. Unburned carbon, and unburned, partially oxidized, organic materials

Hydracarbon combustion is brought about by two different processes: hydroxilation and decomposition.

**Table 3.** Emission of some partially oxidized components in g/Gcal

component	coal combustion		oil combustion		natural gas combustion	
	power plant	domestic and commercial heating units	power plant	domestic and commercial heating units	power plant	domestic and commercial heating units
carbon monoxide (CO)	32	3200	<1	21	negligible	<1
aldehyde (HCHO)	<1	<1	6	21	2	4
hydrocarbon (as CH <sub>4</sub> )	13	640	33	31	negligible	negligible

Hydroxilation occurs when hydrocarbon molecules combine with oxygen to produce alcohols or peroxides that split into aldehydes — mainly formaldehyde — and water. The aldehyde burns to form CO<sub>2</sub> and H<sub>2</sub>O. Decomposition is the process where hydrocarbons are "cracked" into carbon and hydrogen, which burns to form CO<sub>2</sub> and H<sub>2</sub>O.

Both processes occur during combustion in large power stations. Smoke from an oil-burning unit, for example, is the result of incomplete combustion. The chimney plume will then contain carbon, carbon monoxide, aldehyde and hydrocarbons.

Large power plants are usually efficient in operation when controlled and regulated to achieve complete combustion. The emission of unburned or partially burned hydrocarbons is not significant. Table 3 gives the gaseous emission factors for fossil fuel combustion in power plants and domestic and commercial heating units [3].

#### F. Anorganic trace gases

Various salts are found in coal mineral matter, some of which are chlorides and some fluorides.

The British classify coals, with respect to the chlorine content, as follows: high — over 0.3 %; medium — between 0.15 % and 0.3 %; and low — below 0.15 %. The content varies, depending upon the coalfield [4]. Fluorides are mainly present in quantities of 100–400 ppm (by weight).

In combustion a proportion of these salts form HCl and HF, which are emitted. This implies, for coal combustion (depending upon the type of coal) HF emission ranges of 10–40 mg/m<sup>3</sup>, and HCl emission ranges of 10–1000 mg/m<sup>3</sup>.

The sodium present in oil is largely sodium chloride

dissolved in emulsified water, or in suspension in microcrystalline state. Here again, part of the chlorine will be released as HCl, and that in the order of 5–30 mg/m<sup>3</sup>.

#### G. Source distribution of combustion products

The source distribution of air pollutants is at the moment not well defined in European countries. For Western Europe we can use approximately the same values as those given for the United States by the U.S. National Academy of Sciences. Table 4 gives this source distribution in percentages for the United States [5], and also the proportion attributable to power station emissions.

## II. Influence of the fuel on pollutant emission

The combustion of coal and oil in power plants, in addition to releasing nitrogen oxides, fly ash and soot, is a major source of sulphur dioxide emissions. The combustion of natural gas produces only an emission of nitrogen oxides. The total emissions of these various components are primarily determined by the fuel balance.

Table 5 shows the consumption of fuels, for the years 1967–1969 inclusive, for the production of electricity by conventional thermal power stations (both public and industrial) in the EEC [6]. Within this short space of time there was a clear tendency towards a decrease in coal consumption and an increase in the consumption of fuel oil and natural gas. This trend is expected to continue in the future.

**Table 4.** Source distribution in percentages for selected air pollutants in the United States.

Source	carbon monoxide	sulphur oxides	hydrocarbons	particulate matter	nitrogen oxides
transportation	91.7	2.1	64.7	15.0	38.7
industry	2.8	37.8	24.6	50.0	20.0
generation of electricity	0.8	44.5	0.7	20.0	30.0
space heating	2.7	14.8	3.3	10.0	10.0
refuse disposal	2.0	0.8	6.7	5.0	1.3
total	100.0	100.0	100.0	100.0	100.0

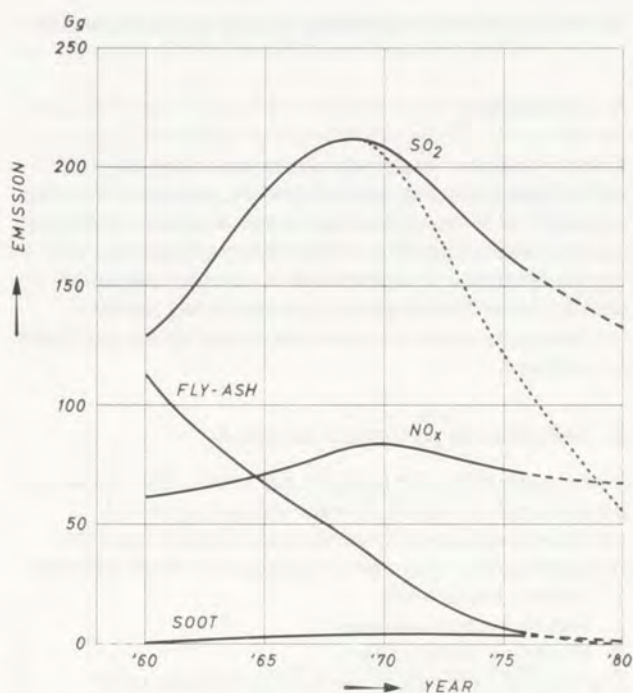
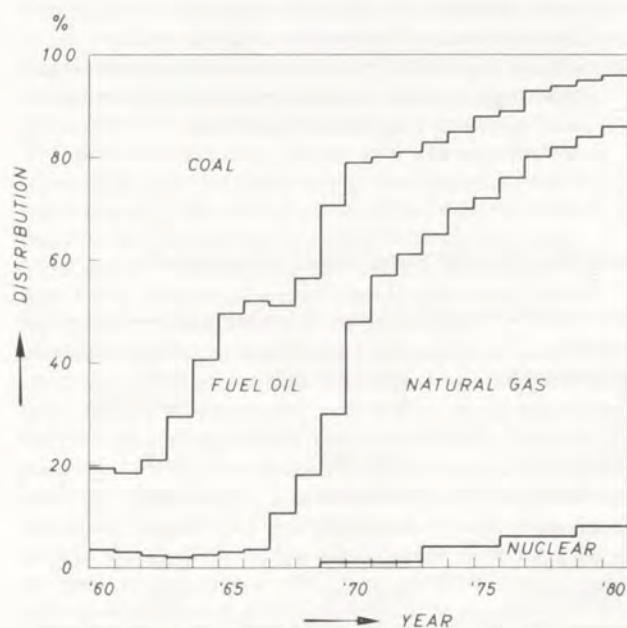
**Table 5.** Consumption of fuels for the production of electricity by conventional thermal power stations in the Common Market countries (public and industrial).

	1967	1968	1969
Total calorie equivalent in Tcal	811,000	870,000	974,000
fuel in %:			
coal	66	63	58
oil	24	25	28
natural gas	4	6	8
industrial gas	5	5	5
waste	1	1	1
total	100	100	100

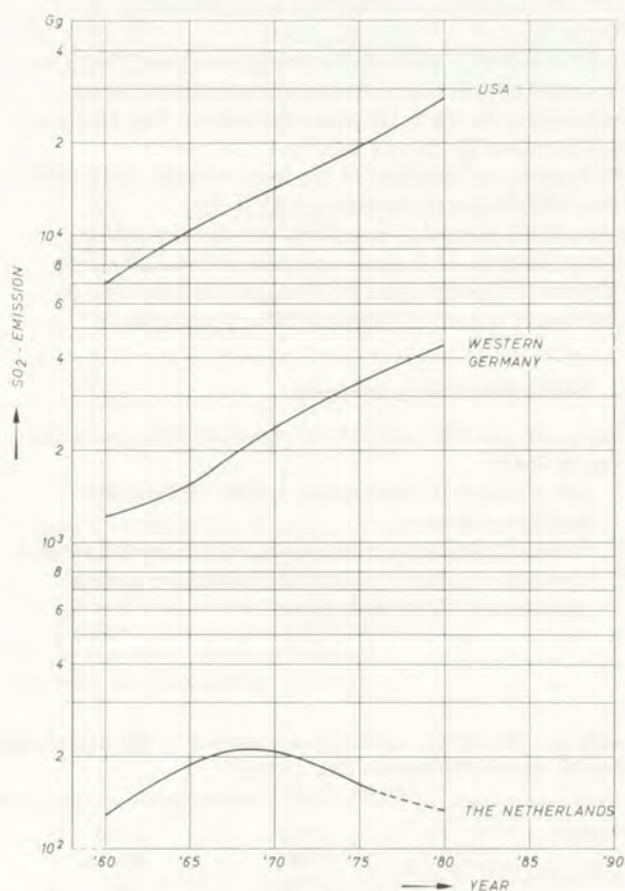
There is, in the Netherlands, a growing use of natural gas for electricity production, as Figure 4 shows. On the basis of rising electricity demand and forecasts of coal, oil and natural gas consumption in Dutch power stations, a calculation was made in 1969 of the future emissions of atmospheric pollutants over the next ten years [7].

Figure 5 gives the results of these calculations, which show that there will be no increase in emissions during the ten-year period. In fact, with the continuing increase in the use of natural gas, the total discharge of air pollutants will actually decrease. The curvature given in the figure for SO<sub>2</sub> is calculated for a sulphur content of the oil of 2.4 % (median value of the oil used in the Netherlands in 1968). If the sulphur content decreased to 1 % in 1980 the fall-off in SO<sub>2</sub> emission would become still more pronounced, as shown by the dotted line.

That this does not apply to other countries can be seen from Figure 6, where the expected SO<sub>2</sub> emissions are given for the United States and Western Germany, as well as for the Netherlands.



**Figure 5 -** Total emission of air pollutants from Dutch power stations (1Gg = 10<sup>9</sup>t).



**Figure 6 -** Total emission of sulphur dioxide from power stations in the United States, Western Germany, and the Netherlands (1Gg = 10<sup>9</sup>t).

**Figure 4 -** Distribution of fuel consumption for power generation in the Netherlands.

### III. Methods of controlling power plant emission

#### A. Introduction

The air pollution problems associated with electric utility plants burning fossil fuels result mainly from the emission of three pollutants: sulphur oxides, nitrogen oxides, and particulate matter. Technologies for the control of these pollutants are in various stages of development. The potential for improving these technologies depends upon the nature of the pollutant in question.

#### B. Reduction of particulate emission

In the case of power stations the particulate matter to be removed is mainly fly ash. Various types of separators are used to remove the fly ash from the flue gases, and they can be grouped in three classes:

1. inertial separators
2. wet collection devices
3. electrical precipitators.

The inertial separators used are cyclones, multi-cyclones, or a combination of both. In these the acceleration provided by the centrifugal force replaces the gravitational force for precipitation. The efficiency of this type of separator is between 70 % and 85 %.

The wet collection devices have an efficiency of 90-94 %.

In the electrical precipitator the gravitational force is replaced by the electrostatic force on the ionized particles in the field between the plates. The efficiency lies between 92 % and 99.8 %.

All separators installed in the Netherlands since 1962 have efficiencies in excess of 92 % [8].

Particulate control is a well-developed technology, and nowadays all but the smallest of the submicron particles of fly-ash can, in principle, be removed by the proper control of high-efficiency equipment.

#### C. Reduction of SO<sub>2</sub> emission

There are several methods of reducing SO<sub>2</sub> emission, among them:

1. substitution of one fuel by another with a low sulphur content.
2. removal of sulphur from fuels before combustion.
3. removal of sulphur compounds (formed during combustion) from flue gases.

4. use of new combustion processes which themselves control the pollution.

Bearing in mind that the production of natural gas, low sulphur oil and low sulphur coal can only meet a small part of the rising fuel demand in the world, we must next turn to the removal of sulphur compounds.

At first sight, the desulphurization of relatively small amounts of fuel would appear to be very much more effective compared with the removal of SO<sub>2</sub> from very large volumes of flue gases. However, it has been established that, for the present, the removal of sulphur from fuel is both difficult and extremely costly. Desulphurization processes for a partial removal of the sulphur in oil are under development in the United States and Japan, and may perhaps result in the delivery of a low-sulphur oil at an acceptable increase in price.

In removing SO<sub>2</sub> from flue gases a distinction is made between wet and dry processes. A serious disadvantage of the wet processes is the low stack gas temperature, resulting in a low plume rise and, in some cases, local ground level concentrations of SO<sub>2</sub> which are even higher than those resulting from non-treated gases.

This difficulty does not apply to the dry processes. However, the relatively low SO<sub>2</sub> concentrations in the flue gases, the large volume and high velocity of the gases, and the required reaction time necessitate very large installations. Throughout the world more than 60 processes have been proposed and are in various stages of development.

Among the post-combustion removal processes, those which show most promise of eventual commercial success are the recovery processes:

- a. *Alkalized alumina process*, developed by U.S. Bureau of Mines.  
SO<sub>2</sub> is adsorbed on pelletized Na<sub>2</sub>O + Al<sub>2</sub>O<sub>3</sub>. Regeneration takes place via hydrogen sulphide to sulphur.
- b. *Cat-ox process* (Monsanto, USA)  
SO<sub>2</sub> is catalytically oxidized to SO<sub>3</sub>, which is condensed to sulphuric acid.
- c. *Reinluft process* (Germany)  
Adsorption of SO<sub>2</sub> on a special activated charcoal. It will ultimately yield sulphuric acid.
- d. *Dap-Mn process* (Mitsubishi, Japan)  
Adsorption of SO<sub>2</sub> on activated manganese oxide. After regeneration the process produces ammonium sulphate and calcium sulphate.

**Table 6.** Preliminary economic evaluations of the capital requirements and gross operational costs for five sulphur dioxide removal processes [9].

Process	plant size MW	load factor %	capital requirements \$	gross operational costs per year \$	gross operation costs mills/kWh
Alkalized alumina	800	90	8.500.000	3.400.000	0.537
Cat-ox	1000	80	25.000.000	5.300.000	0.663
Reinluft	300	47	6.300.000	1.200.000	0.912
Dap-Mn	1000	90	15.500.000	7.500.000	0.931
Kiyoura	600	90	6.700.000	3.700.000	0.762

e. *Kiyoura process* (Japan)

Catalytic oxidation to  $\text{SO}_3$ , which reacts with  $\text{NH}_3$  to form  $(\text{NH}_4)_2\text{SO}_4$ .

Preliminary economic evaluations of these processes indicate capital and gross operational costs as given in Table 6 [9]. These gross operational costs will increase total operational production costs by about 10%. Demonstration control installations using these processes are at present under construction in the United States and Japan.

**D. Reduction of nitrogen oxide emission**

Reducing the nitrogen oxide pollution from utilities by stack gas treatment (scrubbing) appears to have limited practicability as  $\text{NO}$  is insoluble in aqueous bases.

As a result of kinetic and thermodynamic considerations it seems that the best method of reducing  $\text{NO}$  emissions is that of modifying the combustion processes.

Various techniques which have already been tested in the laboratory and on pilot-scale equipment include fluid-bed combustion, low excess air combustion, flue gas recirculation, elimination of air heat, and two-stage or multi-stage combustion. Some of these have also been tested on full-scale equipment in the United States, but reliable full-scale data exist only for natural gas fired boilers.

In the case of two-stage combustion (the introduction of about 10% of the combustion air requirement a few feet downstream of the burner to complete combustion) a reduction in  $\text{NO}_x$  emission of approximately 40% was achieved [10]. Most of the above-mentioned modifications result in a measurable loss of combustion efficiency, with the exception of the two-stage combustion method.

**IV. The dispersion of effluents from tall stacks**

**A. General**

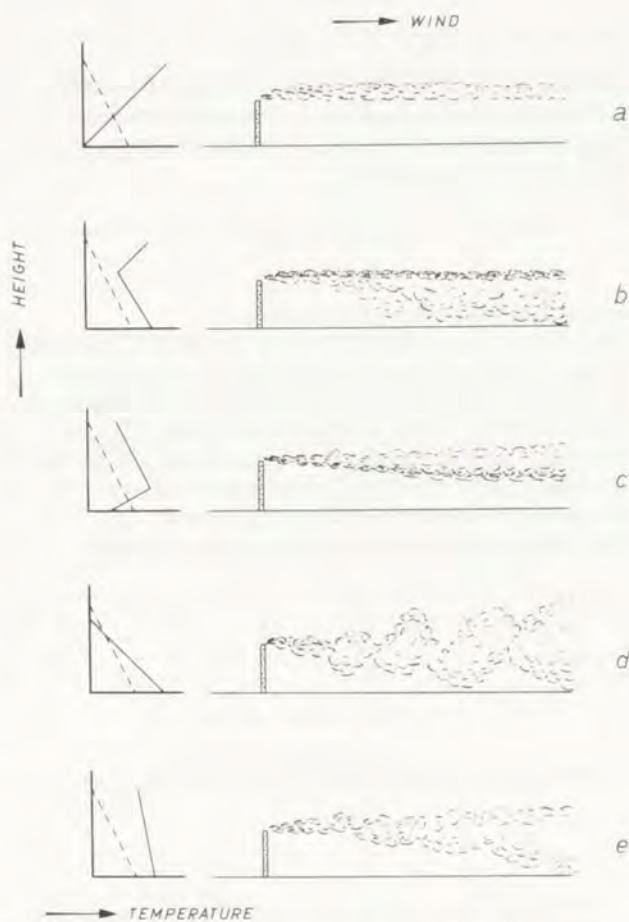
Elevated stacks, which disperse and dilute stack gases before they reach ground level, play an important part in air pollution control. They are effective in lowering the ground level concentration (emission) of pollutants, but do not in themselves reduce the amount of pollutants released into the atmosphere.

The usual concern with power plant stack effluent is, of course, with the maximum ground level concentrations found in the near vicinity of the site, i.e. within the first ten kilometres in circumference. Working formulae or relationships can usually be applied to give fairly satisfactory engineering estimates of the pollutant concentrations to be expected.

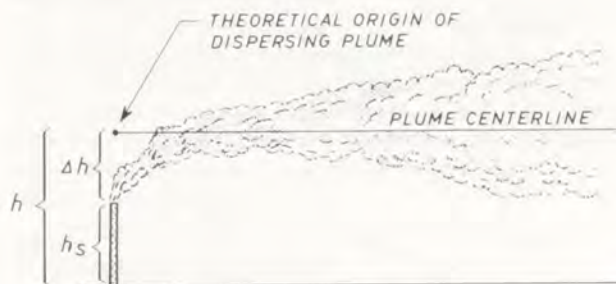
Determining the expected maximum ground level concentrations at various distances from the plant site with various stack heights requires a sound knowledge of the meteorology of the area concerned. Data should be collected on wind direction and speed, atmospheric stability, atmospheric dispersion patterns, and the topography of the surrounding area. To put it very simply, the stability of the atmosphere is its tendency to resist or enhance vertical motion. Stability is related both to wind shear and to temperature structure in the

vertical, but it is generally the latter which is used as an indicator of the condition of the atmosphere.

The behaviour of plumes emitted from stacks is primarily controlled by the stability of the atmosphere, which in its turn is governed by the day-night diurnal cycle. Some types of vertical plume spread related to the temperature profile are given in Figure 7. The dashed line in the temperature profile represents a decrease in ambient temperature with height of  $-1^\circ\text{C}/100\text{ m}$ ; the so-called "potential temperature" is here constant with height.



**Figure 7 - Vertical plume spread in relation to the temperature profile. (dashed line represents dry adiabatic rate)**  
 a. Inversion condition (fanning)  
 b. Lapse below, inversion aloft (fumigating)  
 c. Inversion below, lapse aloft (lofting)  
 d. Strong lapse condition (looping)  
 e. Near neutral condition (coning)



**Figure 8 - Effective stack height ( $h$ ).  $h$  is the sum of the actual stack height ( $h_s$ ) and the plume rise ( $\Delta h$ ).**

## B. Ground level concentrations

In order to calculate the ground level concentrations it is assumed that dispersion begins at a theoretical point of origin directly above the stack. The height of this point of origin ( $h$ ) is the sum of the actual stack height ( $h_s$ ) and the plume rise ( $\Delta h$ ), as shown in figure 8. The plume rise is related to the energy ( $E$ ) — both kinetic and thermal — in the plume, and the average wind speed ( $u$ ). Many equations have been proposed for the calculation of plume rise. They can be expressed by the formula

$$h = f \frac{(E)^{1/3}}{u^2}$$

where  $u$  is the mean wind speed, and the exponent  $a$  is a constant, often equal to 1. The maximum ground level concentration is given by the most commonly used dispersion equation:

$$C_{max} = \frac{2Q}{e \pi u h^2} \cdot \frac{\sigma_z}{\sigma_y} \quad (1)$$

where  $Q$  is the pollutant release rate.

The vertical and horizontal plume standard deviations  $\sigma_z$  and  $\sigma_y$  are functions of distance ( $x$ ), and meteorological conditions. Four plots for the vertical standard deviations of a plume, derived from Smith [11], are given in Figure 9. The power law functions are set out in Table 7, determined for both the vertical and horizontal standard deviations of a plume.

The maximum value occurs at the distance where

$$\tau_z = \frac{h}{\sqrt{2}} \quad (2)$$

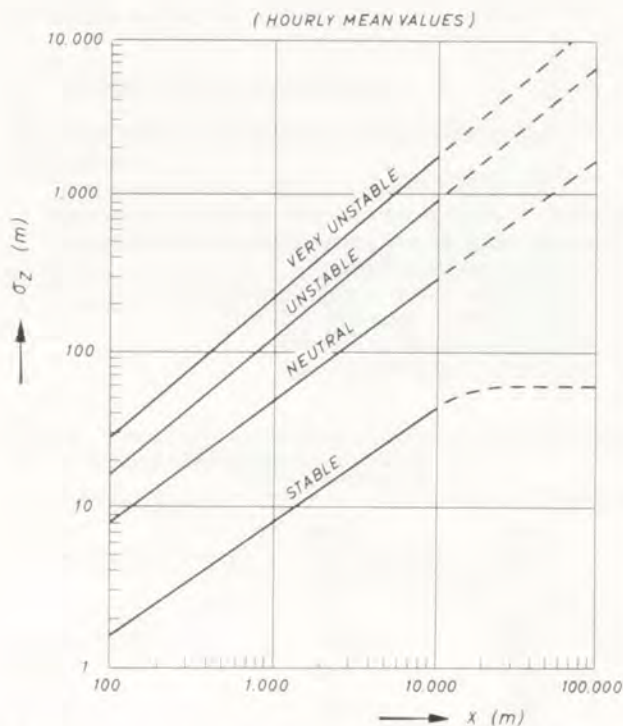


Figure 9 - Vertical standard deviation of a plume, related to distance.

Table 7. Power law equations for  $\sigma_z$  and  $\sigma_y$  in the form  $\sigma = \rho x^q$  ( $x$  in m). [11]

atmospheric stability	$\sigma_y$		$\sigma_z$	
	$\rho$	$q$	$\rho$	$q$
very unstable	0.40	0.91	0.40	0.91
unstable	0.33	0.86	0.36	0.86
neutral	0.22	0.78	0.32	0.78
stable	0.06	0.71	0.31	0.71

To give some realistic data we can take the example of a 250 MW oil-fired unit, using oil with a sulphur content of 1.5% producing an  $\text{SO}_2$  emission of 1800 kg/h. If  $h = 200$  m at a wind velocity of 10 m/s, and the atmosphere is neutral (which produces, from

Table 7, a value for  $\frac{\sigma_z}{\sigma_y}$  of 0.7), we can use equation

(1) to calculate  $C_{max}$ . The result is  $C_{max} = 200 \mu\text{g}/\text{m}^3$ . From equation (2) it can be calculated that this maximum value occurs at a distance of approximately 3700 m.

More unstable atmospheres produce a slightly higher maximum ground level concentration at shorter distances, and more stable atmospheres a lower maximum ground level concentration at longer distances.

A worked example of calculation of the monthly distribution of  $\text{SO}_2$  concentrations around a large modern 700 MW coal-fired power plant is given by Smith [11]. The parameters he used were, among other things, a sulphur content of coal of 3% and a stack height of 183 meters. He evaluated the concentration pattern associated with each hour and added the hourly contributions at many points surrounding the site in order to obtain the mean monthly data. In

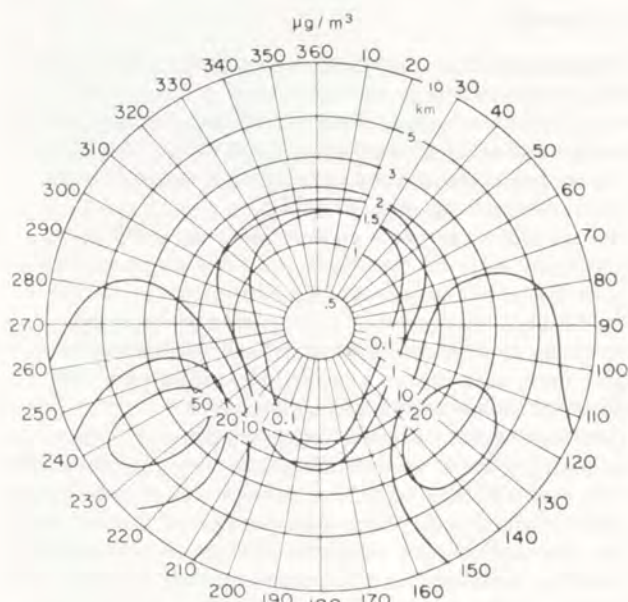


Figure 10 - Monthly distribution of  $\text{SO}_2$  concentrations for a worked example of a 700 MW power station, calculated by Smith [11].

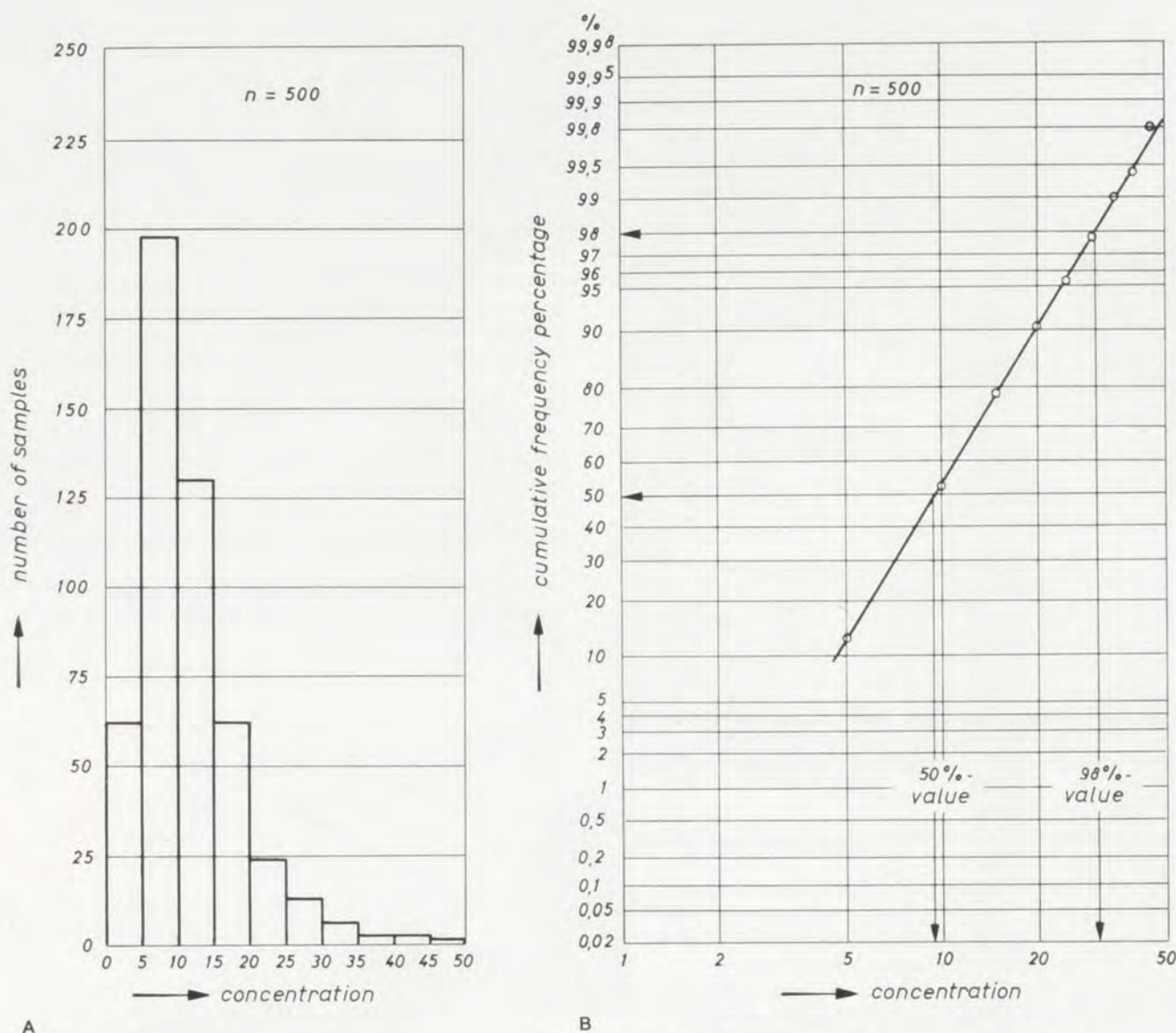


Figure 11 - A distribution of ground level concentrations in arbitrary units (A) and the derived probability line using the lognormal distribution (B).

this example the wind rose gave prevailing wind directions, with 29 % of direction in the sector 30°-90° and 23 % of direction in the sector 270°-320°. The result is shown in Figure 10. Note that the peak values in the mean distribution are only a fraction of the typical hourly maximum which would obtain for this example. Use of a coal with lower sulphur content, 1 % for instance, will reduce concentrations by a factor 3.

In view of the exposure of living organisms to air pollution, we are not only interested in mean long term concentrations, but also in the frequency of occurrence of certain ground level concentrations. From experience it is known that the lognormal distribution function can usually be applied to the frequency distributions of ground level concentrations. Most of them show a distribution which is called negatively skew.

An arbitrary example is given in Figure 11A. The concentrations can also be presented as straight lines in a graph, using a logarithmic scale for the con-

centration and a normal probability scale for the cumulative frequency as shown in Figure 11B. The slope of this line gives an indication of the variation of the pollution.

As a practical example, Figure 12 gives the cumulative frequency distributions of the maximum ground level SO<sub>2</sub> concentrations under the plume axis as measured in the surroundings of three Dutch power stations, each with a different capacity. The next step is to calculate the frequency distributions of concentrations in the surroundings of a power station, and also the probability of exceeding defined concentrations, with the aid of frequency tables of meteorological dispersion phenomena. Such calculation programmes are now being developed in several countries.

### C. Benefit from stack height

Almost every major power plant designed nowadays for fossil fuel has a stack so chosen as to keep ground



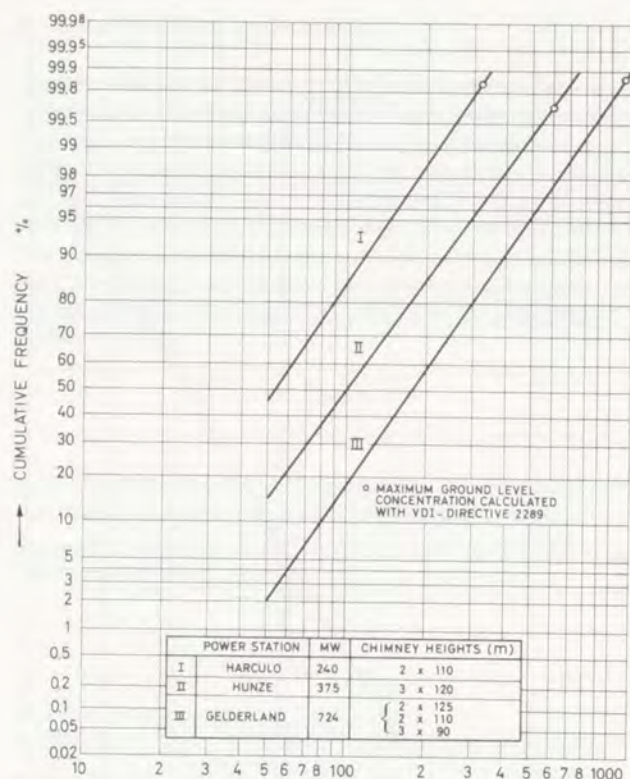


Figure 12 - The maximum ground level SO<sub>2</sub> concentrations (horizontally plotted in µg/m<sup>3</sup>) under the plume axis, as measured in the surroundings of three Dutch power stations.

level pollution within the various limits imposed by the authorities.

Experts do not indeed entirely agree as to the exact degree of benefit resulting from stack height, or the manner in which this benefit can best be achieved, but there can be no doubt whatever about the reality of the effects. Under any meteorological conditions a tall stack located on an open, uncomplicated site will achieve a considerable reduction in the local ground level concentrations when compared with the same emissions released at low levels. This reduction is accomplished simply by giving natural atmospheric turbulence an opportunity to dilute the pollutant before it reaches ground level receptors.

It is also important to realize that a stack located on open ground converts the least favourable meteorological conditions into the most favourable. Within a well-developed temperature inversion the mixing process is extremely slow and ineffective, particularly in the vertical direction. For all practical purposes a

Table 8. The mean value of Q (SO<sub>2</sub> emission) and  $\frac{Q}{h^2}$  for a number of coal-fired units installed in the Netherlands in the period 1954-1965 [8].

Installed capacity in MW	Number of units	Mean value of Q in kg/h	Mean value of $\frac{Q}{h^2} \times 10^4$ in kg/m <sup>2</sup> h
1... 50	14	215	152
51...100	12	480	130
101...150	8	910	108

plume emitted at any reasonable height above the ground in an inversion remains aloft indefinitely, producing no ground level concentrations.

The trend with power generating units is towards a constant increase in individual size. Stack heights are increasing proportionally with plant size in recognition of the need to maintain lower ambient air concentrations. Figures 13 and 14 (see page 26) show two of the newer Dutch power stations with adapted chimney heights.

A practical example of the increasing stack heights is given in Figure 15, showing the relationship between chimney height and plant size for coal- and oil-fired units brought into operation in the Netherlands in the

years 1954-1965. The values of Q and  $\frac{Q}{h^2}$  set out in

Table 8 show the effect of these increasing heights during those years [8].

Bearing in mind that  $C_{max}$  is directly related to  $\frac{Q}{h^2}$

(equation (1)), it can be concluded that, in spite of the increasing emission per unit, the related  $C_{max}$  values are reduced.

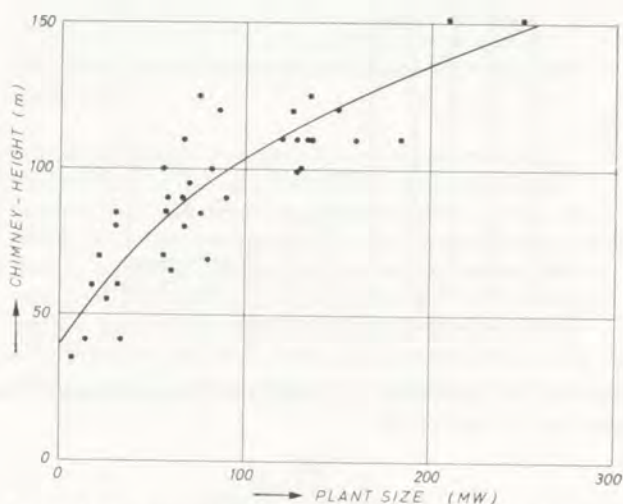


Figure 15 - Relationship between chimney height and plant size (coal- and oil-fired units put into operation 1954-1965 in the Netherlands).

## V. Research and development: future aspects

Control and improvement of the quality of the environment is of growing concern to the industrialized nations. This is reflected in the comprehensive programmes dealing with the environmental aspects of power plant effluents.

One of the primary aims of the clean air policy has always been to minimize the ground level concentra-

Figure 13 - Multiflue 155 m chimney at power station "Velsen". (photograph: PEN archives, 1967).



tion of pollutants. This concentration can be reduced,

remembering that  $C_{max}$  is proportional to  $\frac{Q}{h^2}$ , by

reducing the total emission  $Q$  and/or by increasing the height of emission ( $h$ ). For the main part the measures taken consisted in increasing chimney height. Generally speaking, in 1960 stacks were lower than 100 metres, where now they rise 150 metres or more.

The working equations commonly used to estimate dispersions were derived from field studies involving emissions below 100 metres, and because relevant data on atmospheric dispersion processes at upper levels are sparse — and also difficult to obtain — little information is available which can be related to plume dispersion from the taller stacks. To remedy this deficiency a number of field studies are now under way in several countries.

Increasing pressure has been brought to bear on limiting emissions, which has resulted in a sharpening of the control measures of  $Q$ .

The possibilities of using substitute fuel to reduce the emissions of  $SO_2$ , for instance, are in general limited. The use of the vast reserves of high sulphur coal (particularly in the United States) and of high sulphur oil (particularly in Japan) in the utility market requires the development of a variety of  $SO_2$  removal techniques. It is expected that, especially in those two countries, another 2 to 5 years will pass before one or more of the advanced sulphur dioxide control systems can be considered as proved technologies. They will also partly come into use in some European countries.

It appears, from information currently available in the U.S.A. that nitrogen oxides can best be controlled by altering the combustion processes in such a way as to prevent their formation, rather than by trying to remove them from the stack gases after combustion. Research on, and development of the prevention of nitrogen oxide formation will be directed towards finding a method of reducing nitrogen oxide emission without a measurable loss in combustion efficiency. It is expected that this subject will also require attention in Europe in the near future.

One important factor in the clean air policy affecting the ultimate choice of possible measures is the matter of large-scale effects. The possibility that an increase in atmospheric pollutants would have a significant effect on the climate is under discussion. Thus there has been found to be an actual increase in the  $CO_2$  content of the atmosphere, but the "greenhouse effect", seems to be small. The long-range effects of  $CO_2$  are likely to be reduced, partly because of the buffering action of the ocean, partly because of the increased photosynthetic absorption and storage by forests, while a limit to  $CO_2$  production is also set by the prospective exhaustion of fossil fuels [12]. These discussions have not yet produced final conclusions, which emphasizes the need to obtain improved data on the various substances emitted from large stationary sources such as power stations, and on the reactions and ultimate destiny of such substances in the atmosphere.

In addition to the task of defining the behaviour of plumes from power stations and the dispersion of pollutants on a larger scale, there is a need to examine the chemistry and physics of the dispersed pollutants in the atmosphere, as well as studying the natural atmospheric removal mechanisms for the pollutants.

A definitive evaluation regarding the possible effects of the original and transformed combustion products is urgently needed.

Work in this field is only at an early stage, and should be expanded. Various speculations concerning the effect on climate, for example, are only indicative, and are imprecise regarding the overall impact of anticipated power production requirements. Nevertheless, they emphasize the need to search for and apply positive measures for reducing emissions, and not simply to rely on the dispersion and dilution capacity of the atmosphere.

This view is corroborated by the extensive programmes which have already been initiated to deal with the various matters raised in this chapter.

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## CHAPTER 4. BIOLOGICAL EFFECTS OF COOLING WATER DISCHARGE

by J. L. Koolen

### Summary

*The quality of the surface water must be dealt with carefully. At first a description of the concept of this water quality is given, defined by three parameters: the oxygen, the organic, biologically decomposable matter, and the fertilizer salts contents of the water.*

*Then the influences on the water quality and the biological effects of cooling water discharges are described. The use of surface water, containing a certain living biomass, as coolant, has an influence on the quality of the cooling water itself. The oxygen content may decrease, that of organic, biologically decomposable material may increase, not least caused by the use of antifouling agents like chlorine. The discharge of used coolant to the receiving water has various consequences. In general, chemical and biochemical processes are accelerated. This is the main cause of all water quality and biological effects discussed. The maximum permissible temperature (30 °C in the Netherlands) is mentioned, with respect to the uncertainty about this value.*

*In the receiving water the decomposition of organic matter is accelerated and increased at higher temperatures, including the oxidation of ammonia to nitrate, which reaction only occurs at temperatures above 10 °C. In bottom mud layers the decomposition of organic matter under anaerobic conditions forms bubbles of gas (methane and hydrogen sulphide), which process is accelerated at higher temperatures. So the mud is stirred up and causes further pollution of the water.*

*The biological consequences of the warming up of surface water may be serious, although in many cases no exact values are known at present. But everything is based on the statement that biological life is intensified at higher temperatures. Primary production (phytoplankton, weeds and higher plants) and the production of bacteria and fungi are increased. The vital functions of and in the organisms are intensified, which might lead to disturbance and death. The temperature-dependent propagation of the aquatic organisms might be affected, with the result that the balanced aquatic life as a whole is disturbed. With water and riparian plants the same effect is possible.*

*Quite another effect is the increase in the sensitivity of aquatic organisms to lethal and sub-lethal concentrations of toxic substances at higher temperatures. A low oxygen content in addition makes life hardly endurable for the organisms, as they are being pressed to consume more oxygen. Some additional, special effects due to certain circumstances are discussed. In a stagnant water (although this concept is rather theoretical in large waters) the introduced current, resulting from the water's use as a cooling basin, may cause difficulties. The aquatic life may be disturbed, bottom mud may be stirred up, both with effects as described above. The stronger dilution of discharged waste is an advantage, although the contamination with faecal (and pathogenic) bacteria from municipal wastes might be spread out over a larger body of water. A definite advantage of the introduced current in a water is the increase of reaeration.*

*The use of river water as a coolant must be dealt with very carefully. The large streams to be used must normally be fit for a multi-purpose use, i.e. cooling water, receiving water for (effluents of purified) waste water, drinking water preparation, irrigation water etc. Careful deliberations must prevent one type of use of a river excluding the others.*

*The use of seawater as a coolant also has some peculiarities. Marine organisms are more sensitive to extreme conditions than fresh water organisms. So, much attention must be paid to the mixing of the discharged heat in the sea. The antifouling measures must be dealt with very carefully. On the one hand thorough antifouling methods are necessary, on the other hand the surrounding sea must not receive too many toxic agents. Some recommendations are given for the planning of new (and the regulation of existing) electricity production plants.*

*Anyhow, careful deliberation between all people concerned is essential: the electricity producer, the water manager, the chemist, the biologist, the hydrologist. Some general recommendations are: maximum permissible temperature in the temperate areas 30 °C, control measures; quick mixing of the discharged coolant in the receiving water, hydraulics; no discharge of waste water in a cooling water system; avoidance of too large current velocities in the receiving water.*

## I. Introduction

Until a few years ago the discharge of heated cooling water, particularly from electricity generating stations, was still one of the most innocuous forms of water pollution. Population growth, the relative increase in the use of electricity and the scale increase in the building of new power stations are, however, swiftly bringing about a change in the relationship between the quantities of cooling water used and the quantities of surface water available from which the cooling water is taken and into which it is discharged. For these reasons it is necessary that forecasts and extrapolations be made now for future years. The scale increases have resulted in a situation where more care is, and should be, taken over the building of generating stations as regards their effect on their surroundings. It is also imperative that particular care is — and should be — taken over the quality of the surface water, which is the most commonly used coolant.

Water is, in many of its reactions, a living substance. It is for this quality, due to the biological life present in it, that man uses it, in many ways and in varying degrees of intensity. If something can be utilized, then also misuse is possible. To guard against the latter is the water manager's task, established by or carried out with the backing of effective legislation.

In this chapter the effects, in so far as they are known, of the discharge of large quantities of heated cooling water on the quality of the receiving surface water, will be examined. Also consideration will be given to technical control measures which may be required to prevent undesirable situations arising.

## II. The concept of water quality

Surface water in its natural state, created by precipitation, rarely contains more than trace amounts other than H<sub>2</sub>O. Additional matter is introduced by bottom leaching of substances, natural or man-made, and by the discharge of waste. Water, as such, has no "quality". It is an entirely relative concept, used in comparing different waters, or in contrasting one water before and after a particular purifying process. Water quality criteria are usually established by the content of: oxygen, organic matter, nitrogen compounds, phosphates, various salts, various special organic substances etc. The most important quality parameters of the water resulting from cooling water discharge are primarily the content of: oxygen, organic matter (biologically decomposable, B.O.D.<sub>5</sub><sup>20</sup>), and fertilizer salts (nitrogen compounds and phosphates).

These criteria will first be dealt with in greater detail.

### A. The oxygen content

The gases present in the atmosphere, including oxygen, dissolve in water in certain proportions. Their

solubility decreases as temperature increases. At a pressure of 1 atmosphere the solubility of oxygen in fresh water (the saturation value) is as shown in Table 1.

Table 1

temp. °C	0	5	10	15	20
O <sub>2</sub> g/m <sup>3</sup>	14.62	12.80	11.33	10.15	9.17
temp. °C	25	30	35	40	
O <sub>2</sub> g/m <sup>3</sup>	8.38	7.63	7.1	6.6	

The introduction of oxygen from the atmosphere into water is known as aeration. If the oxygen has disappeared from the water for one reason or another its re-entry is known as reaeration. This is a spontaneously occurring, physical process. The rate at which it takes place is dependent upon the type of water flow (ranging from still pool to waterfall), and upon temperature. It is directly proportional to the degree of undersaturation (the deficiency in respect of the saturation value). The degree of dependence of the reaeration on the type of water flow is illustrated in Table 2.

Table 2

Water type	Reaeration in grams O <sub>2</sub> /m <sup>2</sup> /24 hour period, per % undersaturation
small pool	0.01 - 0.02
large lake	0.04 - 0.05
slow flowing water	0.06 - 0.07
large river	0.09 - 0.10
rapid	0.1 - 0.2

These values are given for a temperature of 20 °C. The rate of reaeration increases 1-2 % with each additional °C.

Apart from reaeration oxygen is also introduced into water via carbon dioxide assimilation. This process is done by phytoplankton, weeds and water plants. As the presence of these organisms is a result of the presence of fertilizer salts, the assimilation effects will be dealt with later.

Oxygen is an essential base material for a very wide variety of biological processes. The aquatic life<sup>1)</sup>, built up in oxygenous water, ranging from micro-organisms to fishes, is dependent on the presence of oxygen. The degree of dependence for the various organisms is not clearly definable. However, a universally accepted criterion for the oxygen content is that fish (in Dutch waters, i.e. no *Salmonidae*) fare

<sup>1)</sup> The terms "aquatic life" and "organisms", used in the text of this chapter include the range which is mentioned here.

noticeably worse in water with an oxygen content of less than 5 g/m<sup>3</sup>, although they can tolerate it for long periods. With a content lower than 3 g/m<sup>3</sup> harmful effects are increased to a marked degree, longer exposure greatly reducing the chances of survival.

### B. The organic matter content

This material can enter the water via natural processes, such as the decay of organisms, and via the discharge of waste. Organic matter is used as food by a large number of micro-organisms, notably bacteria and fungi. Nature requires their help in converting waste organic matter into carbon dioxide and water (among other things), and thus to recirculate. This process is known as self-purification. In oxygenous water the bacterial flora growth implicates the consumption of dissolved oxygen to achieve this conversion process. With a natural supply of organic matter this consumption is rarely so large that it causes inconvenience to other organisms, such as fish. With a supply of organic matter from effluent discharge however, this relationship can be totally upset.

If there is no more oxygen present in the water, the conversion of organic matter continues, but via other groups of micro-organisms which are able to operate under the new conditions. In this way nitrate (NO<sub>3</sub><sup>-</sup>) is converted into gaseous nitrogen (N<sub>2</sub>), sulphate (SO<sub>4</sub><sup>=</sup>) into the toxic and malodorous hydrogen sulphide (H<sub>2</sub>S), and part of the organic matter itself into marsh gas (methane, CH<sub>4</sub>). There is no doubt that these substances do not belong in healthy surface water.

If a certain amount of organic matter is present in the water this matter is converted by bacteria in a rate directly proportional to the concentration of this matter. The quantity which is decomposed per unit of time is thus greatest in the beginning and constantly decreases. As soon as the water is undersaturated, the reaeration process begins, and the greater the undersaturation, the more intensive the reaeration. As time elapses the oxygen consumption due to the conversion of organic matter is decreasing so the oxygen increase from reaeration will eventually predominate.

The result is that in water to which a certain amount of organic matter is added the oxygen content first decreases until it reaches a minimum value, and thereafter gradually rises, finally reaching the saturation value.

The bacterial decomposition of organic matter is so regular, at least in so far as any biological process can be said to be regular, that it can almost be considered as a chemical reaction. For this reason the organic matter content can be determined on the basis of the oxygen consumption of the water in a test bottle under control conditions. These conditions are: temperature 20 °C, period 5 days, complete exclusion of light and air. The difference in the oxygen content before and after the test is called B.O.D.<sub>5</sub><sup>20</sup>: Biochemical Oxygen Demand at 20 °C over 5 days.

The rate of the B.O.D. reaction increases approximately 5 % for each additional 1 °C.

### C. The fertilizer salts content

This heading covers nitrogen compounds such as ammonium and nitrate, and phosphates. In water their effect is similar to that on land. They stimulate the growth of green plants: phytoplankton, weed and water plants, to a marked degree. This growth can become too exuberant if the concentrations of nitrogen compounds and phosphates are too high. Starting with only 1 gram of PO<sub>4</sub><sup>-</sup> and 6 grams of NH<sub>4</sub><sup>+</sup> (or 20 grams of NO<sub>3</sub><sup>-</sup>) approximately 40 grams of vegetable matter can develop.

Mass growth of phytoplankton can seriously upset the delicate balance of aquatic life. Generally only a few plankton species will multiply excessively, crowding out the other species. Mass growth of higher plants (weeds, floating or rooted water plants, and riparian plants) can result in the water becoming completely overgrown, causing an acute deterioration in the living conditions of the other organisms.

Oxygen is formed by the growth of vegetable organisms, according to the well known photosynthetic reaction:



This phenomenon is often considered a benefit for water quality. However, if organisms so formed die off later, this reaction is reversed. Then almost the same amount of oxygen is required as had been formed in the first reaction. Thus the overall effect of algae formation is nil.

So much oxygen is produced by excessive phytoplankton bloom that the water becomes oversaturated and gives off the gas to the atmosphere. As these organisms die off the water once again comes to contain so much organic matter, which is automatically cleared up by the self-purification process, that the oxygen content declines sharply, so an equal amount of oxygen must again be captured from the atmosphere. It can even go so far that the water becomes totally deoxygenated.

Moreover living phytoplankton also consume oxygen. In the daytime this is not such a problem as they produce enough themselves. At night however, when this production ceases, their concentrated oxygen demand can have disastrous consequences for other oxygen-consuming organisms such as fish. These same phenomena appear in the higher vegetable organisms. In addition, an abundance of floating plants, duck-weed for example, can just about entirely prevent reaeration and the entry of light into the water, causing serious difficulties for the normal aquatic life.

So one can say in general that a moderate presence of vegetable organisms (stimulated by slight amounts of phosphates and nitrogen compounds) is favourable, because of their oxygen production and their function as food for higher organisms. However, due to the presence of higher concentrations of fertilizer salts, an excessive amount of phytoplankton and higher plants can develop very quickly, making the water, as regards its oxygen content and the living conditions for other organisms, very unstable and disagreeable. Therefore, in general fertilizer salts must be considered harmful in their effects.

### III. The consequences of discharging heated cooling water

#### A. The effect on the cooling water itself

##### 1. Decrease in the oxygen content

The cooling water used in a modern electric power station undergoes a temperature increase amounting to 6–8 °C as a rule. This causes a decrease in the saturation value of the dissolved oxygen in the water. Saturated water will thus, by being heated, give off oxygen to the atmosphere. In the summer this can amount to: 9.17 g/m<sup>3</sup> at 20 °C minus 8.07 g/m<sup>3</sup> at 27 °C giving a release of 1.10 g/m<sup>3</sup>. In winter this would be: 13.84 g/m<sup>3</sup> at 2 °C minus 11.59 g/m<sup>3</sup> at 9 °C giving a release of 2.25 g/m<sup>3</sup>.

When the oxygen content of the intake water is lower than the saturation value for the temperature of the discharged water, there will generally be no oxygen decrease. It is also possible to introduce special measures which supply oxygen to heavily under-saturated water in a power station.

##### 2. Increase in pollution from organic matter

Cooling water that passes through a power station is subjected to many mechanical processes. The water flow is turbulent, and it is reasonable to suppose that organisms carried along in the water are not all able to survive this treatment. Plankton in particular, with their delicate and graceful forms, would be easily damaged, and injury to unicellular creatures causes their death in many cases.

The result can be the formation of dead organic matter, which must later be cleared up by the bacteria in the water with a consequent oxygen consumption, and which must therefore be considered as pollution. There are indications that these effects are less serious with larger generating units.

##### 3. Effect of antifouling agents

An aggravation of the above effects is caused by the fact that antifouling (= toxic) substance, usually chlorine, is either continuously or intermittently injected into the cooling water pipe system. The inevitable result is that a proportion of the living matter (plankton) flowing along in the water is killed, and thus converted into organic pollution.

It is therefore good to promote the use of mechanical methods of antifouling (*Taprogge*-system).

#### B. Fundamental effects on water quality as a consequence of the use of surface water as coolant

##### 1. Acceleration of the chemical and biochemical processes, maximum permissible water temperature

All chemical and biochemical processes are accelerated; by a factor of 1.5–3 per 10 °C rise in temperature. This is the basis underlying all the phenomena to be examined below. The acceleration continues with rising temperature; in such a way that the higher the temperature, the more unstable the processes become. More and more disruptions arise which can eventually kill off the organisms concerned. In this way the acceleration of the biochemical processes is overtaken at a certain moment by the lethal action of

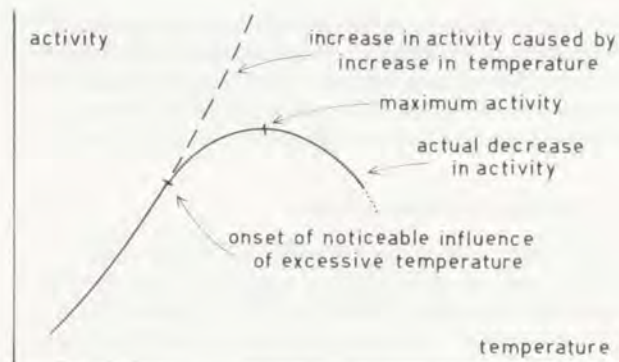


Figure 1 - Relationship between biological or biochemical activity and temperature.

the high temperature. This is illustrated in Figure 1. The temperatures for these phenomena vary widely for different organisms. But it is frequently found that temperatures in excess of 32–36 °C will kill water organisms in the temperature zones in a relatively short time. Therefore a temperature of 30 °C has been temporarily established as being the maximum permissible temperature both for surface water and for the cooling water to be discharged into it. There are indeed organisms known to be unable to tolerate even this temperature (for example fish species such as *Salmonidae*). But there are still no known data to indicate that this temperature would be unacceptable to the aquatic life in the waters mentioned.

Two points must be emphasized. First and foremost, it is not yet certain that this maximum value of 30 °C will continue unchanged for ever. Research (begun in The Netherlands and other countries) will have to prove whether it is a permissible value. It is not impossible that this limit will have to be lowered in a few years time. Secondly, it would be unwise to expect that the value of 30 °C will be significantly increased. If 32 °C should be a lethal barrier, for example, a permitted temperature of 30 °C is already very high. It is possible to illustrate this by comparing the effect of temperature with that of a toxic substance. If a substance in a concentration of, let us say, 1 g/m<sup>3</sup> is lethal, that still does not mean that the water may be loaded with the substance to a value just below the lethal figure (0.8 g/m<sup>3</sup> for example). For a number of reasons the water manager needs to observe wide safety margins.

##### 2. Chemical and biochemical consequences

###### a. Decrease in the saturation value of oxygen in water

The decrease in the saturation value of oxygen in the receiving water resulting from the discharge of cooling water is not so spectacular as that which takes place in the cooling water itself. (see III. A. 1). The discharged cooling water is diluted with unused surface water, and the temperature naturally drops. If the discharged cooling water already has the saturation value corresponding to its temperature, then the question arises whether, and to what degree, the mixing of cooling and surface waters also causes further oxygen loss. The curve of saturation value against temperature is, over a span of 8 °C, practically linear. Comparison of water quantities, temperatures

and oxygen contents show that further oxygen loss does not take place.

b. *Acceleration of the decomposition of organic matter*

It has been mentioned earlier that the rate of the B.O.D. reaction increases approximately 5% with each additional 1 °C temperature rise. This means that the oxygen consumption per unit of time increases. The total oxygen consumption becomes even greater as a result of the increase in the decomposability of some compounds.

The rate of reaeration increases 1–2% per °C rise in temperature. The oxygen undersaturation corresponding to a particular oxygen content decreases 1.5–3% per °C rise in temperature. Reaeration is proportional to the degree of undersaturation. Taking all these factors together it can be seen that the reaeration at different temperatures varies only little in numerical terms.

The end result is that the decomposition of organic matter takes place more sharply at higher temperature. There is a greater decrease in oxygen content than there is at lower temperature. Moreover, this decrease takes place earlier in the period considered, and can also be corrected earlier. Figure 2 illustrates this.

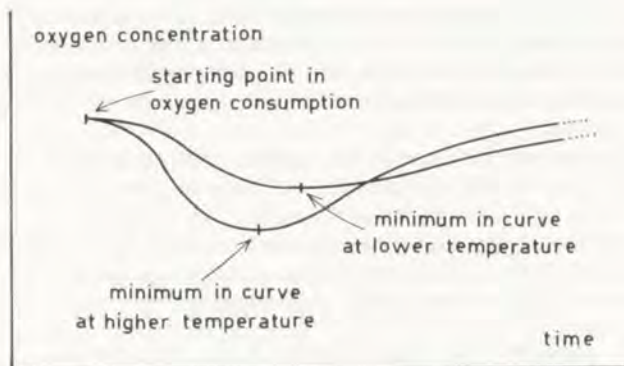


Figure 2 - Influence of temperature on oxygen consumption curve.

When living conditions of oxygen-dependent organisms are concerned, the minimum oxygen content must be considered the limiting factor. For this reason a higher temperature must be considered relatively harmful.

One advantage is that the pollutants are more quickly and completely cleared up. An example of this is the decomposition of phenol, which originates in the petrochemical industry. Substances in this group (aromatics) are extremely troublesome. They taint the flavour of fish and cause difficulties in the preparation of drinking water from surface water. They are only slowly broken down by the self-purification processes, but this decomposition is intensified by higher temperatures.

c. *Oxidation of ammonium to nitrate*

Ammonium ( $\text{NH}_4^+$ ) is a breakdown product of the conversion of organic wastes in a sewage purification plant or in surface water. It is also found in the aquatic world as a result of its use as an artificial fertilizer on the land.

There are groups of bacteria which are able, with the aid of oxygen in the water, to oxidize ammonium to nitrate ( $\text{NO}_3^-$ ), these are the so-called nitrifying bacteria. In this reaction, of course, oxygen is consumed from the water. This consumption is not included in that arising from the conversion of organic matter, the B.O.D. reaction.

The oxidation of ammonium takes place neither as smoothly nor as predictably as the B.O.D. reaction. For this reason calculations, such as those used in the B.O.D. reaction, are almost impossible. Only when the ammonium content is higher (several  $\text{g/m}^3$ ; the level in nature being 0.01–1  $\text{g/m}^3$ ) a noticeable oxygen decrease may result.

It is a well-known fact that the oxidation of ammonium is temperature-dependent. It only takes place above 10 °C, so it is a summer, and not a winter phenomenon. The result of warming surface water by cooling water discharge is that on the one hand the period within which the resultant oxygen consumption occurs is extended, and that on the other hand the reaction will be accelerated, with a consequent increase in oxygen consumption per unit of time.

Since these results all contribute to bringing the oxygen condition of the water one step nearer to a critical level they must be considered as having a harmful effect on water quality.

d. *Increase in the decomposition of bottom mud*

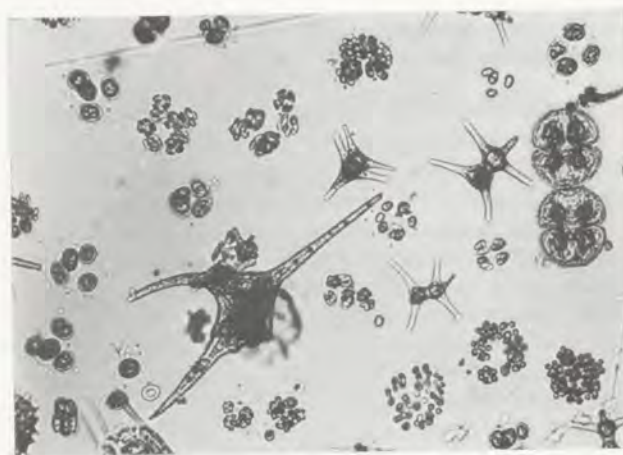
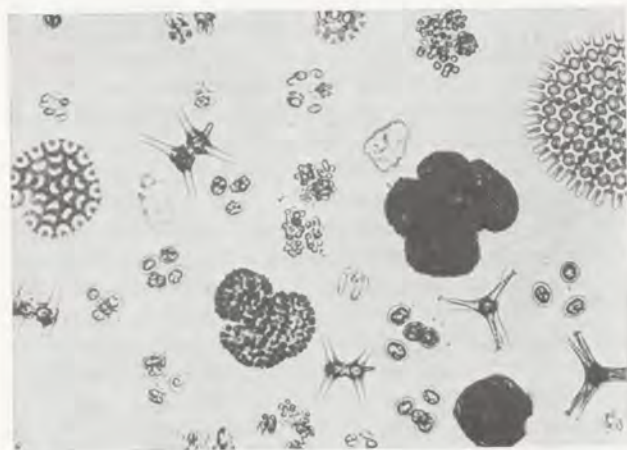
The mud in most standing waters, particularly shallow canals and lakes, contains a great deal of organic matter, which slowly decays. As oxygen from the water above does not generally penetrate very far into the mud layer, the decomposition of the organic matter in the mud occurs for the most part under oxygen-free conditions. In this way gases may be formed, among them methane and hydrogen sulphide. Increasing the temperature accelerates all reactions. So both the production and rate of production of the gases in the deeper oxygen-free mud layers will increase. It is known from the fermentation of sludge in sewage purification plants that this increase as regards the quantity of gas, is 4–8% per °C (above 25 °C : 1–3%); and as regards the speed of fermentation is 6–10% per °C (above 25 °C : 2–4%). The result of an increased gas development in decaying mud layers is that the mud is stirred up by gas bubbles and brought into suspension, giving the water above a greatly increased amount of organic matter to dissimilate. This again makes demands on the oxygen. In addition, the poisonous hydrogen sulphide also comes into the water at the same time. These phenomena are met with on very hot summer days, often in shallow polluted waters, accompanied by widespread fish deaths. It is evident that such a situation is far from ideal, and it should be borne in mind that raising the average water temperature in polluted water increases the chances of it occurring.

3. *Consequences for aquatic life*

a. *Increase in the primary production and development of bacteria*

The primary production, i.e. the production of phytoplankton from water, carbon dioxide, fertilizer salts and trace elements — that is to say from anorganic





Figures 3 and 4 - Mixtures of plankton (Photos R.I.N., State Institute for Nature Management, Zeist)

compounds — is stimulated by higher temperature, as is the growth of bacteria based on organic waste. These two types of organism are in great demand as food for higher life forms, which are, in their turn, eaten by those next above, and so on up the scale. This food chain in the water ends with the predator fish or, more accurately, with the animals who in turn live off them. The entire biota is thus intensified by the increase in the basic food source. If the food exceeds a certain level the intensification becomes so excessive that it can disturb the balance of water life. In addition the instability in the oxygen content mentioned earlier is encouraged by an over-exuberant flourishing of phytoplankton.

*b. Effect on the vital functions of aquatic organisms*

These vital functions are accelerated. Activity is increased in many respects, particularly in the assimilation of food and in the production of energy. This phenomenon can be put to very good use in fish farms, where the supply of heated water can solve many problems, particularly in winter. Fish growth can be greatly accelerated for market purposes. There is, of course, also a growing chance of some organisms living "too intensively" (see also Figure 1). Sudden temperature increases, in particular, can be disastrous in this respect.

*c. Effect on the propagation of aquatic organisms*

The propagation of many species of organism is activated by temperature rise (springtime), so an artificial temperature rise will obviously have a disturbing effect, changing the normal behaviour of organisms for the time of year. Different organisms can react in different ways to a rise in temperature. If the various species under natural conditions are in harmony with each other, i.e. living off each other, these different changes may have an adverse effect on the aquatic life as a whole.

*d. Changes in the aquatic population structure*

What has been described above may cause some species of organism to die off, and others to appear in their place. Therefore changes in the population structure can be expected.

For fishes it is known that these changes may range from species which belong in oligotrophic, or perfectly

clean water (i.e. *Salmonidae*), to species which can live in more eutrophied, or even slightly polluted water (*Cyprinidae* for example).

*e. Changes in the population structure of water and riparian plants*

Like plankton, water and riparian plants can begin to display a faster and more exuberant growth as a result of increased water temperature. On the other hand the currents in the cooling circuit may inhibit such growth. The growth and blooming of riparian plants will be able to move to earlier periods in the season.

Just as with the aquatic life itself this can lead in the long run to alterations in the structure of the plant cover along the banks of the water. The question is whether these alterations can be evaluated. It is quite possible that a sharp temperature rise could bring about a marked reduction of the flora.

*f. Increase in the sensitivity of aquatic organisms*

Broadly speaking, the sensitivity of aquatic organisms to probably all harmful factors in the water increases with higher temperatures. There may be an effect on lethal or sub-lethal concentrations of toxic substances, oxygen deficit, etc. In particular, endurance of low levels of oxygen content is reduced. This is linked with the fact that, at higher temperatures, cold-blooded organisms are forced to dissimilate more food and so to consume more oxygen. Should decrease in free oxygen supply happen anywhere (in this case by the low concentrations in the water), then the various species will arrive at a physiological conflict situation, which can have extremely serious consequences. Therefore, a temperature increase must be considered harmful to fish, for example, in addition to all the other adverse factors such as oxygen undersaturation, sub-lethal concentrations of toxic substances, etc.

**C. Additional consequences of currents induced in a lake used as a coolant source**

*1. Changes in the types of organism present*

In perfectly stagnant water the aquatic life, such as plankton, invertebrates and fish, is based on the absence of current. If, in such waters, a continuous

current is introduced, as would happen if they are to form a part of a cooling circuit, then there will undoubtedly be certain species unable to adapt, and they will disappear. In the long run they will be replaced by species which belong in flowing water, and which for that reason were absent before.

The effects of these changes will not primarily affect water quality, but they are certainly important as regards the scientific value of the life in the water. Most lakes in The Netherlands serve as storage basins for polder water, and as such are frequently streamed to a greater or lesser degree. Moreover windflow across large lakes can result in considerable current velocities. The qualification "perfectly stagnant water" is thus far from applicable to all lakes.

#### 2. *The caving in of banks and the stirring up of bottom mud*

Large lakes at present in The Netherlands are situated in flat areas, where the ground may have a loose composition of peat, clay, or sand. The introduction of a current here can have disastrous effects on the water banks. Earth can cave in, or be worn away and carried along in suspension in the water.

It is also probable that, in shallow waters (only a few metres deep), currents will stir up bottom mud, which will likewise be carried along in suspension. Currents in excess of 0.3–0.4 m/s are likely to bring this about. The mud in many shallow lakes, particularly in those lakes situated in cultivated areas where the discharge of sewage and the use of artificial fertilizers on the land have resulted in a certain eutrophication of the water, contains a great deal of organic matter. Currents stirring this matter up can have much the same results as already outlined in III. B.2.d.

The muddying of previously "clear" lakewater can have a positive effect in preventing the excessive flourishing of phytoplankton. Apart from the food already mentioned, a great deal of sunlight is required for this process, and an abundance of mud particles can restrict its penetrability for light. For the rest, the transition from clear to muddy water can definitely bring about important changes in the population structure of aquatic life, as described above in III. B.3.d.

#### 3. *Dilution of discharged sewage*

Discharged sewage, which can bring about such a poor water quality in standing water, are relatively highly diluted in running water. The adverse effects are thus spread out over a wider area and are thereby reduced in absolute terms (the oxygen decrease, for example, is slighter). From this point of view, therefore, a current in the water can be beneficial. An exception to this is the contamination by sewage bacteria. These also are more highly diluted in running water than in standing water, but this dilution must be very high indeed before the bacteria can be disregarded. Sewage contains, among other things, 100,000–1,000,000 coliform bacteria per  $\mu\text{m}^3$  (milliliter). These non-pathogenic bacteria, because of their abundance, are used in many countries as test organisms for assessing the suitability of surface water for swimming. Depending on the country concerned, the standards are that no more than 1–10 of these bacteria be present per  $\mu\text{m}^3$  (milliliter) of water.

The introduction of currents in standing water into which sewage is discharged can thus result in a far greater body of water being made unsuitable for swimming than previously was the case.

#### 4. *Increase in reaeration*

One unarguably beneficial result of increasing current speed in a surface water is the increase in reaeration. Values for this have already been given in II.A.

#### D. **Additional consequences of using river water as cooling water**

Only large rivers can be considered as a coolant source for modern electric power stations, which use scores of cubic metres of water per second. Such a river will almost never be used exclusively for cooling purposes, but will have a wide variety of other uses at the same time. These include its use for drinking water preparation, for irrigation of agricultural land, as a way for the run-off of surplus rainwater, as waterway for shipping, and as receiving water for wastes — purified or otherwise.

The latter use in particular can cause a deterioration in water quality. River water generally contains, as a result of current flow, a good deal of silt and sludge, mostly of natural origin. From modern agricultural areas surplus artificial fertilizers are carried away in rainwater and have a eutrophying effect on water quality. The predominant source of pollution is normally the discharge of sewage, of domestic or industrial origin, which may or may not have been purified.

Large rivers have attracted settlement since time immemorial, and have transformed many places along them into centres of population, with a consequent effect on water quality. It is now precisely in these areas that much water is needed, and therefore much attention must be paid to its quality. This will mainly result in fairly thorough purification of discharged sewage. However, even then, large rivers in most places will ultimately continue serving as receiving water for the effluents from sewage purification plants, and thus receive the residual pollution (about 10% of the original organic matter). This cannot be directly eliminated by the purification plants, and must be further dealt with by the self-purifying processes in the river water itself.

In addition, the river becomes contaminated by fertilizer salts as waste matter in sewage: about 10 g  $\text{PO}_4^{---}$  per inhabitant per day (of this 40–50% is removed in a purification plant), and about 13 g N (mostly  $\text{NH}_4^+$ ) per inhabitant per day (of this 50–70% is removed in the plant). In addition there are also discharges of difficult or unpurifiable wastes from (chemical) industries.

In the large population centres these wastes can cause such a pollution of the river, that the water quality along hundreds of miles, can give the water manager a great deal of trouble. This is simply the result of historical development. In such cases an effort must be made, by more extensive purification and other control and/or technical measures to bring the water quality back to an acceptable state.

It must be emphasized here that such waters must be dealt with very carefully. Their aquatic life is disturbed, unstable, and strained.

The water quality in polluted large rivers, measured by the oxygen content, is definitely worse in summer than in winter. This is caused on the one hand by the lower river run-off in summer, and on the other hand by the accelerated and increased decomposition of all sorts of waste matter caused by the higher temperatures, which results in even more oxygen being withdrawn from the water. (see III.B.2.b and c).

Siting many large power stations on such a river, resulting in considerably higher average temperatures, both in summer and winter, will merely reinforce the adverse summer situation as regards water quality, and extend the periods in which this occurs. The instability of the water quality will, of course, increase still further. For this reason much thought must be given to the planning of electric power stations. Associated studies will have to be carried out to ascertain the correlation between the increased electricity production, the increased river temperature and the water quality.

Should a large river continually have to serve a multitude of uses, as outlined above, then a careful assessment must be made as to whether the various forms of use, including use as cooling water, are not mutually exclusive nor give rise to unacceptable conditions of water quality.

The larger the part of the river run-off required to pass through a power station as cooling water (rain rivers in dry periods!), the more careful the above assessment must be made. For example, chlorination would have to be discontinued in favour of alternative, mechanical antifouling methods.

#### **E. Additional consequences of using seawater as coolant**

##### *1. Sensitivity of seawater organisms*

Most seas are highly stable water masses which grow slowly warmer in the spring and grow slowly cooler in the autumn. Their chemical composition is, as a rule, perfectly constant. The stability of the sea milieu is in many ways much greater than that of fresh water, extreme situations being more rarely encountered. This is a natural phenomenon, and the seawater life is adapted to it. The general impression is that seawater organisms are less able to withstand extreme conditions than are freshwater organisms, this applying particularly to abnormal temperatures or temperature fluctuations.

As the aquatic life in the sea must not be too much disturbed by the discharge of heated cooling water, the latter should be discharged in such a way that the heat is as quickly dispersed and released as possible. It is generally the case that the surfaces and quantities of seawater available are sufficiently large to enable this to take place easily. But the attendant civil engineering problems are not so simply dealt with.

Under certain circumstances the sea can even profit from heated cooling water, namely in heating nurseries for fish, crustaceans and testaceans. Harsh winters can be disastrous for these cultures, with everything freezing to death. This could be counteracted by discharge of warm water. Accelerating growth for market purposes would be an additional benefit, as mentioned in connection with fresh water fishes. (III.B.3.b)

##### *2. Antifouling effects and difficulties*

In seawater the fouling organisms are usually larger than those in fresh water. This applies particularly to sea-weeds, sea-acorns, mussels and other testaceans, all so large that they can cause serious blockages and impairments of pumps, cooling water channels and pipes. It is essential that this spontaneous growth be rigorously combated. Chlorination is the most commonly used method (the chlorine can be produced in the power station itself by means of seawater electrolysis). A continuous low degree of chlorination, to an excess in the order of 0.1 g/m<sup>3</sup>, is much better than an interrupted supply of several g/m<sup>3</sup>, as the mussels etc. can close themselves when the conditions in the water are not good.

The discharged cooling water will contain a certain residual amount of chlorine that will affect the receiving water. Generally, part of the material taken up in the intake water (plankton) will be dead, and will have been converted into organic matter which must then be broken down in the water, with consequent oxygen consumption.

Altogether an intensive chlorination of salt cooling water is very harmful, especially if it is a matter of scores of hundreds of cubic metres of water per second, which will generally be the case with power stations sited on the sea. So an effort should be made to use as little chlorine as possible. The disadvantages mentioned can be corrected by a quick and effective dispersion of the discharged cooling water in the receiving sea, spreading the effects out over a large area and thereby reducing their harmfulness in terms of absolute size. This completely accords with what was said in the previous paragraph.

##### *3. Effect of seawater stratification in estuarine areas*

A more or less physical phenomenon, that also has biological aspects, is the salt-stratification of seawater along a coast where large rivers discharge. The cooling of discharged water takes place on the water surface. It is therefore necessary so to choose the intake water that the specific gravity of the discharged heated water is small enough to enable it to remain on the surface. Should it travel as an intermediate layer in the seawater, then the heat can only, as a rule, be further given up with great difficulty. Only mixing with the layers immediately above and below will then be possible. In such cases the discharged calories remain longer in the water than is either necessary or desirable.

Choosing the intake and outfall points with care will prevent this problem arising.

The advantages and disadvantages of using surface water as a coolant, which have been discussed in III.A through to III.E are summarized in Table 3.

#### **IV. Recommendations**

First and foremost it must be said that the system of electricity generation in use up to now, whereby more energy in the form of waste heat is released to the environment (primarily the water environment) than is

**Table 3.** Summary of advantages and disadvantages of using surface water as a coolant.

Subject	Phenomenon	Advantage	Disadvantage
III.A: effect on the cooling water itself	III.A.1: decrease in the oxygen content	with highly undersaturated water an increase can take place	appears in (almost) saturated water
	III.A.2: increase in pollution from organic matter	no	formation of dead matter, drain on oxygen content
	III.A.3: effect of antifouling agents	no	formation of dead matter, drain on oxygen content
III.B: general effects on water quality	III.B.1: acceleration of biochemical processes	see below	relative, with respect to the natural situation
	III.B.2.a: decrease in oxygen saturation value in water	no	not noticeable, due to influence of III.A.1
	III.B.2.b: acceleration of decomposition of organic matter	faster clearing up of matter hard to decompose, such as phenol	greater drain on oxygen content
	III.B.2.c: oxidation of $\text{NH}_4^+$ to $\text{NO}_3^-$	no	drain on oxygen content
	III.B.2.d: acceleration and increase in mud decomposition	no	drain on oxygen content
	III.B.3.a: increase in primary production and development of bacteria	only on behalf of III.B.3.b	increased instability of water quality
	III.B.3.b: acceleration of vital functions of aquatic organisms	accelerated growth in fish farms	relative, with respect to the natural situation; can lead to irregularities and death of the organisms
	III.B.3.c: interference with propagation	no	relative, with respect to the natural situation; the mutual dependence of organisms can be upset
	III.B.3.d: changes in species balance of aquatic organisms	no	relative, with respect to the natural situation
	III.B.3.e: changes in species balance of aquatic and riparian plants	no	relative, with respect to the natural situation
III.B.3.f: increase in sensitivity of organisms	no	yes	
III.C: effect of introduction of current into standing water	III.C.1: changes in species balance	unbalanced growth can be countered	relative, with respect to the natural situation
	III.C.2: caving in of banks, stirring up of mud	unbalanced growth of algae can be countered	drain on oxygen content
	III.C.3: dilution of discharged waste	spread out effect, making disadvantage — in the absolute sense — less large	contamination of larger areas with faecal pollution
	III.C.4: increase in reaeration	yes	no
III.D: use of river water as cooling water	III.D: use of river water for many different purposes	see III.B all points	increase in instability of water quality, chance of defeating multipurpose use
III.E: use of sea water as cooling water	III.E.1: sensitivity of seawater organisms	accelerated growth of edible organisms	relative, with respect to the natural situation
	III.E.2: effect of antifouling agents	no	formation of dead matter, drain on oxygen content
	III.E.3: seawater stratification in coastal areas	should be used to effect fast cooling	choice of suitable places for taking in and discharging cooling water

generated as electricity, could hardly be called ideal. From the point of view of profitability, there is already a necessity to continue looking for an increase in the efficiency of electricity production, and also for an acceptable use for the resultant waste heat. That at the moment principally surface water is saddled with the latter must be seen as a necessary evil, a part of modern life as much as other factors affecting the environment such as waste matter, noise, disturbance, visual spoliation of the environment, etc. In all these cases there needs to be unremitting effort towards improvement, the production of waste heat not excepted.

Emphasis should be laid on the fact that a large proportion of the influences sketched out in the foregoing sections are (as yet) impossible to quantify.

It is only possible to show tendencies and orders of magnitude of the changes brought about in the water by waste heat. And even where calculations are possible the necessary reservations must still be made as to the exactness of the results.

Extensive physical, chemical, and above all, biological research is necessary before an evaluation of all the effects will be possible. One advantage is that the results of these studies will also be of use in other problems related to water quality research. However, even when all the consequences of heating surface water are known it will not be practicable to make exact computations, on account of the complex character and unpredictability of the physical, chemical and biological factors in the water.

For this reason the water manager would do well to be cautious about admitting relatively large quantities

Figure 5 - Electric power plant 'IJsselcentrale', at Harculo (Photo Jan van de Kam)



of hot cooling water into surface water under his care. It often happens that the larger waters considered for cooling purposes must, at the same time, be fit for a wide variety of other uses, so priorities must be assessed in order to protect essential uses from encroachment. This assessment demands of the water manager wide-ranging preliminary deliberation, study and attendance of recent developments.

As a result supplementary measures: further purification of sewage, the creation of separate cooling circuits, or the building of cooling towers, might have to be taken in order to maintain the surface water at optimum suitability for its uses.

A few general recommendations follow. They are based on the premise that the situation occurring in the surface water concerned must be disturbed as little as possible. Notice that they specifically concern waters in the temperate zones.

#### A. Maximum permissible temperature

The temperature of the water discharged by the power station, and that of the receiving surface water should under no circumstances exceed 30 °C. The temperature at various important points (certainly at the station inlet and outlet), should be continuously monitored. Should the temperature at a particular point threaten to exceed the permissible level, measures should be taken in time. This can be done by reducing electricity production or by using a larger amount of cooling water (not by mixing the overheated discharged water with cooler water!).

The quality of the receiving water should be regularly inspected.

In the ad hoc Study Group on Water Conservation of the Council of Europe there is a paper on cooling water problems under consideration at the moment, in which it is intended to limit surface water temperature to a maximum of 25 °C. This demand, originating from Switzerland, is often impracticable for waters in other countries. However, for waters upon which high demands are made (direct extraction for the preparation of drinking water, recreation) the recommendation has to be emphasized.

#### B. Mixing of discharged cooling water with the receiving water

The discharged cooling water should be mixed as soon as possible with a relatively large quantity of receiving water. In this way temperature is reduced without waste of time, giving the indigenous water flora and fauna the best possible chance of holding their own. The hydrographic and hydraulic conditions around the discharge point therefore deserve close attention.

#### C. Discharge of sewage

The discharge of sewage into a cooling circuit, and also into waters in open communication with it, should be avoided at all costs. In the optimum situation the water in the cooling circuit has absolutely no contact with water from elsewhere, and thus effectively leads its own existence. This situation, however, can only seldom be realized practicably.

#### D. Current velocity

The current velocity in a shallow cooling circuit should not exceed 0.1–0.2 m/s, in order to avoid stirring up bottom mud. Checks should be made that the banks of such waters are themselves equal to this speed.

Should these recommendations give rise to the establishment of (expensive) measures, there may be the feeling that they are based rather on probabilities, trends and orders of magnitude than on precise calculations of the effects to be prevented. It may be said that, when it is a matter of life itself, no risks should be taken. Similarly the same criterion has to be applied when it is a matter of the quality of life.

In conclusion it can be remarked that, in The Netherlands, a close contact exists between a coordinatory organization of the electricity producers, and the manager of the principal waters considered for the cooling of large generating stations, namely the State. The cooling water aspects of every power station planned are discussed and examined in depth, in close collaboration between the electricity producers (regional and coordinatory), water managers (Municipalities, Polder Authorities, Provincial Authorities, and the State), advisory bureaus and research institutes. All these contacts are supported, on the scientific side, by a working group of representatives from the electricity producers and the State, together with biologists and chemists from various institutes in the Netherlands engaged in surface water research.

These forms of cooperation have developed over the last two to three years. It is perhaps uncalled for to recommend this working method to other countries. Particularly on account of the international contacts on cooling water problems which have been developing recently (for example, over the use of one river by several countries), it is greatly to be hoped that the same thorough handling of these problems may become more widely applied.

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## CHAPTER 5. BIOLOGICAL EFFECTS OF AIR POLLUTION

by P. E. Joosting and J. C. ten Houten

### Summary

*Exposure of living organisms to sulphur dioxide, sulphuric acid, fly ash, other particulates, and oxides of nitrogen is discussed from the points of view of air pollution phenomenology, specific and nonspecific responses of plants, animals and man, and environmental and constitutional factors that influence the mode of response and the degree of effect. Some examples of dose|effect relationships are given. For sulphur dioxide and (black) suspended matter (as indices of pollution from the use of fossil fuels) both tolerable and unacceptable criteria are tentatively suggested for the purpose of planning and control. In addition argument is given — from the biological, physiological and common sense standpoints — in support of the concept of clean air conservation.*

### I. Introduction

The effect of atmospheric pollutants upon living material is determined by a number of factors:

- physical and chemical properties of the pollutant;
- its concentration;
- duration of exposure;
- environmental conditions;
- susceptibility of the organism;
- locus and mode of uptake;
- metabolism and rate of elimination.

The latter is of particular interest in the case of human beings and many animal species: a great number of substances may pass through the body or can be eliminated, in their original form or as a detoxified metabolite. Vegetal life usually has no such facilities at its disposal, although a type of elimination of non-physiological substances may take place, e.g. by transporting sulphates into the roots after the leaves have been gassed with sulphur dioxide.

In view of the biochemical rules and probabilities that determine life's fundamental processes, it should be recognized that most pollutants can be characterized as "unknown" and strange to the natural system, either as substances *per se*, or in the concentrations encountered. This means that life in modern environments has to cope with a great number of chemicals that are irrelevant from the point of view of nutrition and energy demand.

Therefore those substances can be considered toxic or potentially noxious, and to get rid of them requires biological energy on the part of human, animal, and plant life. Detoxification and elimination processes happen to take place at the expense of an essentially limited potential of life's phenomena. Consequently pollution problems should be appreciated in terms of body burden and loading capacity, which can be assessed partially on the basis of objective, or of subjective and arbitrary criteria.

The toxicity of a substance can only be assessed if duration and pattern of exposure are known. Therefore a thorough knowledge of air pollution phenomenology is of fundamental assistance. Of a number of pollutants, such as sulphur dioxide (SO<sub>2</sub>) and suspended particulates, it is known that their ground level concentrations per measuring station fluctuate according to a pattern that is reproducible over longer periods, namely an approximately normal (= Gauss) distribution of the logarithms of 24-hour averages over a year (vide chapter 3, section IV)

In agglomerations with a spread of a great number of different sources of varying output, the geometric standard deviation of such a distribution of SO<sub>2</sub> data, for example, is in the order of 1.5. In the case of a measuring station near to a single source — such as the stack of an isolated power station — this figure will be in the order of five.

In practice the net result may be that the geometric mean of both distributions differs to an extent of a factor ten, although on the other hand the probability of excessively high concentrations over a few days per year may be of the same order in both instances.

Although the response of living material is theoretically dependent on the integral of a pattern of exposures, the exposure can in practice be fairly accurately characterized by the mean concentration and the number and level of peak concentrations of short duration. Although no exact relationship exists between extremes of exposures, for practical purposes one may assume that, within a definite range of exposures and with not too toxic substances, the degree of effect will be more or less consistent, depending on the constancy of the product of log concentration and log exposure time ( $E \sim k \cdot \log C \cdot \log T$ ).

Substances that are capable of causing damage to living material and that originate from the burning of fossil fuel in power plants are SO<sub>2</sub>, nitrogen oxides, fly ash and other suspended particles. A relatively small amount of sulphuric acid (H<sub>2</sub>SO<sub>4</sub>) may be emitted.

Some part of the  $\text{SO}_2$  emitted into the atmosphere will be converted into  $\text{H}_2\text{SO}_4$ . This process is dependent on the presence of catalytic particulates (fly ash, metal salts) and on the relative humidity of the plume and the ambient atmosphere. It is reasonable to assume that under normal conditions about 5% (10% at most) of the emitted  $\text{SO}_2$  will be converted into  $\text{H}_2\text{SO}_4$ . Although the latter is precipitated fairly rapidly by growth of the hygroscopic droplets, these sulphuric acid aerosols should not be neglected as an important factor in the causation of damage to living and non-living material.

## II. Effects on plants and vegetation

### A. General

The effect of pollutants upon living organisms depends on several factors, as has been pointed out in the previous paragraph. In the case of plants an important role is played by the great differences in susceptibility existing between various species of both cultivated and wild plants, and even between varieties or individual specimens of some species, in exceptional cases. Moreover, the influence of environmental conditions such as climate, radiation or soil chemistry and moisture, is far more pronounced than in the case of man and the higher animals. These influences vary, however, according to the types of pollutants involved. In this respect the scope of the present survey is rather limited.

In cases of coal burning especially, particulate matter contributes to undesirable deposits on vegetables and fruits. Although direct injury is seldom caused, the harvested product must be cleaned before marketing.

This has financial consequences for the grower. In areas with greenhouses and dutch lights, solid deposits may considerably reduce the amount of light passing through the glass coverage, thus diminishing growth and crop yields.

However, gaseous pollutants are of greater importance — particularly sulphur dioxide and, to a lesser extent, nitrogen oxides. Some countries like the Netherlands are in a fortunate situation from the agricultural point of view: natural gas, which is free of sulphur compounds, is available for heating purposes and electric energy production. For so long as this short-term source of energy is not exhausted it offers an alternative to coal or mineral oil as a fuel in areas where current sulphur dioxide concentrations might be particularly unacceptable.

### B. Sulphur dioxide ( $\text{SO}_2$ )

Careful investigations of the influence of various environmental factors on the susceptibility of plants to sulphur dioxide have resulted in some firm conclusions. Meteorological and soil conditions play an important role as to the degree and amount of damage caused by certain concentrations of  $\text{SO}_2$  present in the air over known periods of exposure. A high humidity increases the susceptibility of plants: from 30 to 60% relative humidity (R.H.) there is a gradual increase, and between 60 and 90% R.H. a rapid increase. The influence of temperature is less pronounced.

So after fumigation with  $7 \text{ mg/m}^3$  (2.5 ppm)  $\text{SO}_2$  for two hours, barley (the most susceptible cereal) can be damaged at an ambient temperature of  $1.5^\circ \text{C}$  and 75% R.H. In the same experiment no damage occurred at  $10.3^\circ \text{C}$  and 45% R.H., but this lack of effect was probably the result of the low humidity alone.

Figure 1 - Chambers for short term experiments with plants exposed to relatively high concentrations of test gases.



Figure 2 - Exposure chambers for the administration of very small gas concentrations to plants during a whole growing season.







Figure 3 - Leaf damage in normally grown tomato plants, due to a six hour fumigation with  $4.2 \text{ mg/m}^3$  (1.5 ppm)  $\text{SO}_2$ .

The amount of sunlight has no clear influence upon the effect of  $\text{SO}_2$ ; this in contrast to what has been observed in the case of plant damage due to peroxyacetylnitrate (PAN), which is the product of a chain of photochemical reactions and an important constituent of atmospheres with an oxidizing (Los Angeles) type of pollution. So far as  $\text{SO}_2$  under experimental conditions is concerned, the plants of lucern (alfalfa) appear to be most susceptible about four hours after sunrise, on both sunny and cloudy days. With spinach and radish the same phenomenon has been observed. Experiments concerning the influence of soil moisture on the effect of fumigation with  $\text{SO}_2$  have shown that vine plants, for example, can be badly damaged if the soil is constantly kept moist, whereas, even after several fumigations with high concentrations ( $4.5\text{--}9 \text{ mg/m}^3$  or  $1.6\text{--}3.2 \text{ ppm}$ ) of  $\text{SO}_2$ , no damage has been observed to plants grown on a dry soil. Similar results have been obtained with tomato plants. In colza the resistance to  $\text{SO}_2$  increases with the mineral nitrogen content of the soil.

Acute symptoms of  $\text{SO}_2$  injury are clearly visible in the interveinal leaf tissues which collapse and later become desiccated and bleached, while the veins themselves remain green. With small doses of  $\text{SO}_2$  no symptoms occur as a rule, because  $\text{SO}_2$  is metabolized, in the leaves, into sulphates which are at least partly transported towards the roots. If small amounts of  $\text{SO}_2$  are absorbed over longer periods, the leaves may become chlorotic.

Epiphytic lichens and mosses (bryophytes) are much more susceptible than higher plants. At an annual average concentration of  $\text{SO}_2$  above  $45 \text{ } \mu\text{g/m}^3$  ( $\sim 0.016 \text{ ppm}$ ) only some species, such as *Parmelia*

*saxatilis*, may survive. Therefore lichens may be used as indicators for the presence of  $\text{SO}_2$ . As a concentration of  $100 \text{ } \mu\text{g/m}^3$ , may, in the long term, adversely affect pine trees, landscape designers should be advised to be wary about planting conifers in a *Parmelia saxatilis* "desert".

Sulphur dioxide can act as a synergist in the causation of damage by ozone. This has been clearly demonstrated in American fumigation experiments using low concentrations of either pollutant, individually as well as in combination.

### C. Nitrogen oxides

As a rule, the nitrogen oxides which are formed in the combustion process of conventional power plants will consist in part, of  $\text{NO}_2$  at the point of maximum ground level concentration. In short term experiments this gas may cause the same symptoms as  $\text{SO}_2$  if high concentrations (about  $5.4 \text{ mg/m}^3$  or  $3 \text{ ppm}$ ) are used. In the outdoor atmosphere such concentrations of  $\text{NO}_2$  rarely occur under normal conditions. In the Netherlands the former have only been found after, say, an accident at a chemical factory. At low concentrations (of about  $0.2\text{--}0.5 \text{ mg/m}^3$  or  $0.1\text{--}0.3 \text{ ppm}$ ) visible effects on tomato plants only appear after a continuous fumigation for several months (Figure 4). However, growth and production may be seriously affected, and can lead to a decrease in yield as high as 22%. In some densely populated areas of the USA a concentration of  $0.5 \text{ mg/m}^3$  (or  $0.3 \text{ ppm}$ )  $\text{NO}_2$  is registered quite regularly. In Western Europe the  $\text{NO}_2$  levels are much lower, and it seems improbable that the emissions from electric power plants will contribute



Figure 4 - Defoliation in tomato plants as a result of a four month continuous exposure to 0.25 ppm of  $\text{NO}_2$ .



Figure 5 - Control culture to the experiment illustrated by figure 4. Grown under the same conditions but without exposure to  $\text{NO}_2$ . Some normal old age effects are visible.

substantially to the buildup of ambient  $\text{NO}_2$  levels that may be hazardous or adverse to plant life. Only if the atmospheric conditions are favourable for the formation of photochemical oxidants like ozone, does  $\text{NO}_2$  act as a "catalyzer", contributing to the ozone-forming process.

### III. Effects on man and animals

#### A. General

As mentioned already, man and his domestic animals have a reasonable capacity to metabolize substances that are "strangers" to the physiology of their systems. Thus they can cope with a stream of biologically irrelevant information. But there are limits, as has so clearly been demonstrated during so-called smog disasters — periods of a few days with adverse meteorological conditions causing cumulation of pollutants (for example, during the heating season). During such periods (and sometimes shortly after-

wards), a lesser or greater number of particularly vulnerable people appear to be afflicted, as shown by increased mortality, sickness rates and functional impairment (cf. Greater London 1952 with 4000 excess deaths in a few days, at an expected death rate of about 300 per day during wintertime). As to the causation of the nonspecific health effects in cumulation periods with a reducing type of pollution, the following substances are suspected to play a role: sulphur dioxide, black suspended matter (soot), and other particulates — amongst which sulphuric acid aerosol and sulphates. Although not routinely measured, carbon monoxide (from open fires, stoves with stagnating chimney flow, traffic) could also have played a part during these periods.

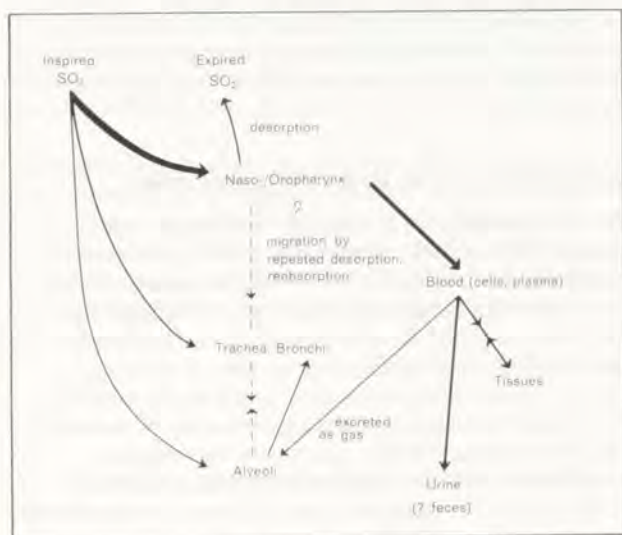
On the one hand it is to be expected that under such circumstances sufferers from chronic bronchitis and those with impairments of the cardiorespiratory system would be the main potential victims. On the other hand it is surprising just how disastrous the effects have in fact been, when it is considered that they resulted from exposure to polluted atmospheres which in practice could only be characterized by such con-

centrations of  $\text{SO}_2$  and particulates as have failed to demonstrate any unfavourable effect under comparable circumstances, like industrial exposures and experiments with human volunteers and animals. One should recognize the fact that  $\text{SO}_2$ ,  $\text{H}_2\text{SO}_4$ ,  $\text{NO}_2$ ,  $\text{CO}$ , and particulates are the only measured indicators of an amalgam of pollutants that is, in effect, more toxic than can be deduced from the presence of only one or a few parameters.

Various substances may interact, or even separately potentiate their respective responses. In this respect it is very well known that small particles with a diameter of less than five microns can penetrate deep into the airways and lungs, where they may irritate and evoke responses of an obstructive nature, depending on the acid gases or liquids adhering to the particle surface. Mucus production and reflex constriction of the smaller bronchi and bronchioli, together with the increased airway resistance and impaired breathing in respiratorily crippled and sensitive people, is a typical result of exposure to these essentially nonspecific stimuli.

One should not be surprised if future investigations bring fresh facts to light that lead to new concepts in this field, as is the case with the latest ideas on the uptake and metabolism of  $\text{SO}_2$  in the body. A few years ago  $\text{SO}_2$  was only appreciated as an external agent that could irritate the mucous membranes of the airways when inhaled.

Modern investigations with tracer techniques and balance studies of uptake and output have shown that  $\text{SO}_2$ , being an easily soluble gas, is 90 to 100 % absorbed in the aqueous surface of the mucous membranes of the nose and throat (nasopharynx). From there it is transported through the tissues into the blood stream. In various organs an accumulation of labeled sulphur molecules can be measured. After



**Figure 6** - Outline, based on experimental evidence, suggesting different paths taken by  $\text{SO}_2$  after its removal from inspired air. Thickness of arrows is intended to indicate roughly relative amount of sulfur moving along each path. Whether  $\text{SO}_2$  migrates along mucosal surfaces from nasopharynx or oropharynx to larynx and lower airways is unknown as is indicated by broken line.

Frank, N.R., Yoder, R.E., Brain, J.D., and Eyi Yokoyama:  $\text{SO}_2$  ( $^{35}\text{S}$  Labeled) Absorption by the Nose and Mouth Under Conditions of Varying Concentration and Flow, Arch Environ Health 18 : 315-322 (March) 1969.)

some time  $\text{SO}_2$  appears in the expired air and is thus excreted, in a proportion not yet quantified (vide Figure 6).

A great deal of the energy transport in the body is performed by (de-) hydration of sulphhydryl ( $\text{HS-}$ ) groups. One may assume that inhaled and circulating  $\text{SO}_2$  influences this system. This has in fact been shown in experiments in which  $\text{SO}_2$  reduced the capacity of the total  $\text{HS-}$  system in the blood of test animals. That this mechanism does not directly result in catastrophic sequelae under experimental conditions can probably be explained by the fact that for energy transport a number of reliable systems normally act together to keep a balance by compensatory mechanisms. A loss of vital energy can thus be camouflaged in healthy organisms, where in ill or disabled people it would become readily apparent.

Considerable attention has been paid to the relation between mean and peak concentrations of  $\text{SO}_2$  and (black) suspended matter on the one hand, and the mortality pattern in the population on the other. So far relatively well qualified and quantified dose/effect relationships have only been evaluated under exceptional circumstances, in which pollution levels over one or two days either raised current concentrations fourfold, or greatly exceeded definite thresholds. Such evaluations have also been attempted for morbidity parameters such as hospitalization, absenteeism, outpatient attendance and subjective responses of patients, mainly with reference to respiratory and cardiovascular symptoms.

As to the causation or promotion of adverse health conditions due to atmospheric pollutants, it is probably unrealistic to think in terms of specificity and direct cause and effect relationships. The observed symptoms and deteriorations of man's health are not a representative response to the influence of any one particular agent, and likewise, one substance may evoke different types of response (cf.  $\text{SO}_2$ ,  $\text{H}_2\text{SO}_4$ , nitrogen oxides, particulates, and cigarette smoke, versus chronic bronchitis, lung emphysema, and lung carcinoma). It should be mentioned in passing that it is an established fact that inhalation of cigarette smoke is the main contributor to the causation, promotion and continuation of this type of disease. Compared with the detrimental effect of cigarette smoking, the influence of air pollutants from combustion processes in their normal emission concentrations, can probably claim only 10 % of the joint influence of both these features of modern civilization!

There are indications that, among children and young people in polluted areas, alterations of the functional condition of airways and lungs may appear in a degree which would not in itself be so serious, but that in the long term could facilitate the onset of recurring respiratory infections. One of the nonspecific — but very typical — effects that has been observed in animals in polluted atmospheres is an acceleration of the aging process, which can be described as an accelerated, uneconomic and regardless consumption of life's potentials, and even of life itself!

The fact that  $\text{SO}_2$  and other gases can be registered by the olfactory and central nervous system at con-

centrations so small that they are sometimes far below the sensory threshold, has been demonstrated by investigators whose work is informed by the concepts of the prominent Russian physiologist I. Pavlov and of V. A. Rjazanov, the late hygienist. Unconditioned (= natural) as well as conditioned (= acquired) reflexes appear to be altered in the course of particular standard tests. The electroencephalogram (= record of the electrical activity of the cerebral cortex) appears to reflect subsensory registrations of changes in the composition of the atmosphere. With increasing concentration of the test gas an initial rise in the cortical activity can be observed, followed by a decline. Although these findings look spectacular, it has not yet been evaluated precisely what practical significance they have as regards the possible inhibition of brain function. But one should recognize the fact that human individuals, as well as the community as a whole, have increasingly to rely upon the integrity of their sensory and intellectual information processing system.

### B. Sulphur dioxide (SO<sub>2</sub>)

The threshold for smell detection of SO<sub>2</sub> lies at a concentration of about 3 mg/m<sup>3</sup> (~ 1 ppm). Unpleasant irritation may occur at a level of 5–6 mg/m<sup>3</sup> (~2 ppm). Nevertheless, the generally accepted threshold limit value (TLV) for pure SO<sub>2</sub> in industrial working conditions is 13 mg/m<sup>3</sup> (5 ppm). One should note that a TLV refers to time-weighted concentrations for a 7 or 8-hour workday and a 40-hour workweek. Because of wide variation in individual susceptibility however, a small percentage of workers may experience discomfort at concentrations at or below the TLV, with a smaller percentage being affected more seriously by aggravation of a pre-existent condition or by development of an occupational illness. Notwithstanding the relatively solid basis underlying the TLV, it is possible to register, among healthy volunteers in experimental conditions, an increase in airway resistance after only a short exposure to SO<sub>2</sub> concentrations at the TLV. Although the working mechanism of SO<sub>2</sub> is still under study (vide Figure 6), it is possible that reflex responses may play a role in the constriction of the smaller bronchi. On the other hand, irritation of the mucosa does induce an increased mucus production which is an especially deleterious effect in bronchitics, who are liable to react on exposure to concentrations much lower than the TLV, e.g. in the order of 3 to 6 mg/m<sup>3</sup> (1 to 2 ppm) of SO<sub>2</sub>.

Whereas in the outdoor atmosphere other pollutants like fly ash and black suspended matter are nearly always present, one should be aware of interactions between SO<sub>2</sub> and various other substances before attributing a recorded harmful effect to the influence of a single substance like SO<sub>2</sub>. In practice the presence of soot and particulates seems to play an important role. Although the latter need not induce a response *per se*, it has been possible to record unwanted respiratory symptoms in bronchitic patients who were incidentally exposed to an atmospheric pollution that could be characterized by a level of about 1 mg/m<sup>3</sup> (~ 0.4 ppm) SO<sub>2</sub> under presence of only 200 µg soot per m<sup>3</sup>. Although such concentrations of these two substances

do not, in practice, occur regularly in areas with single sources equipped with an appropriate control technique, one should avoid considering SO<sub>2</sub> as being a substance with such a low toxicity that it can be neglected. Especially since it has become clear that SO<sub>2</sub> is absorbed completely and rapidly into bodily organs and systems, the question as to the vital significance of this omnipresent pollutant should be answered, and rapidly.

### C. Sulphuric acid (H<sub>2</sub>SO<sub>4</sub>)

A H<sub>2</sub>SO<sub>4</sub> aerosol is, in terms of S-equivalent, far more irritating and harmful to the respiratory tract than is SO<sub>2</sub>. The response and effect depend on the particle diameter, or, in other words, the deposition area in the respiratory tract. Particles in the order of 1 µm diameter or smaller are very active. At concentrations of about 400 µg/m<sup>3</sup> irritation of the upper airways occurs. Exposure of bronchitic patients to H<sub>2</sub>SO<sub>4</sub> concentrations of 250 µg/m<sup>3</sup> may induce unpleasant irritation and shortness of breath. In healthy people a concentration of 120 µg/m<sup>3</sup> over a limited exposure period would not give rise to clinical symptoms. Although the working mechanisms of SO<sub>2</sub> and H<sub>2</sub>SO<sub>4</sub> are different, experiments have shown that both substances contribute equally in evoking the same type of response. So it is a question of simple addition.

It should be mentioned that other aerosols, like sodium chloride or finely dispersed metal salts, also have the capacity to stimulate an SO<sub>2</sub> effect. In the case of catalytic metal compounds in particular, it is a question of the real H<sub>2</sub>SO<sub>4</sub> formation in the inspired air, or at the surface of the mucous membranes where the agent enters and induces the response.

This is of particular significance where a solitary source such as a power station is contributing, with its SO<sub>2</sub> emissions, to the formation of H<sub>2</sub>SO<sub>4</sub> in a neighbouring area where considerable amounts of catalytically oxidizing substances are present in the atmosphere, as in the case of steel plants and metallurgical works.

### D. Fly ash and other suspended particulates

Fly ash consists of a part of the incombustible minerals of the fuel, i.e. silicates and a great number of metal compounds. Other products, particularly of incomplete burning, may adhere to fly ash particles. For the time being fly ash as such is not a suspect material from the health point of view. It is possible that the metal compounds play a role as condensation nuclei and catalysts in the transformation of absorbed SO<sub>2</sub> into H<sub>2</sub>SO<sub>4</sub>. If these, extremely hygroscopic, particles are small enough to be inhaled (diameter < 5 µm), fly ash may then play a role as a vehicle for the deposition of H<sub>2</sub>SO<sub>4</sub> in the respiratory organs. Attention should be drawn to the presence of polynuclear hydrocarbons in soot from mineral oil combustion because of the interest some of these compounds have from the point of view of carcinogenesis in experimental animals. Although soot is not fly ash, it is thought that such carcinogenic hydrocarbons may well be adsorbed upon or absorbed in fly ash particles.

Apart from this no information concerning the direct

influence of fly ash upon the health of man and animals is available. This must be considered a serious lacuna in the present state of knowledge.

As regards the influence of suspended particulates in general, it may be stated that, among bronchitis, an increase in respiratory distress has been observed during exposure to incidental cumulations of pollutants that could be characterized by daily mean levels of smoke in the order of  $200 \mu\text{g}/\text{m}^3$ , which roughly corresponds to a total amount of suspended particulates of  $400 \mu\text{g}/\text{m}^3$ . Such peak values of particulates can be encountered in areas that have a long term mean pollution level of about  $75 \mu\text{g}/\text{m}^3$  of OECD standard smoke or about  $150 \mu\text{g}/\text{m}^3$  of suspended particulates.

There will probably be no harmful effects observed among sensitive people if the mean level of suspended particulates over the long term remains below about  $70 \mu\text{g}/\text{m}^3$ , which roughly corresponds to  $35 \mu\text{g}/\text{m}^3$  of OECD standard smoke.

#### E. Oxides of nitrogen

Oxides of nitrogen will increase in significance as an indicator of atmospheric pollution. Although they could, in this respect, be ranked with sulphur dioxide, the two can not be compared as regards the predictability of harmful effects on living organisms. Here nitrogen dioxide is of greatest importance. It irritates the mucous membranes, and in higher concentrations may cause irreversible damage to the lungs with immediately fatal consequences (lung edema). Nitrogen dioxide is an oxidizing agent, and as such can denature tissue proteins, even at relatively low concentrations. It induces irreversible and stable chemical bonds which interfere with the vitality and adaptability of elementary structures on cellular and tissue level. Results of recent research indicate that long term exposure to concentration of  $\text{NO}_2$  below  $2 \text{ mg}/\text{m}^3$  (1 ppm) denatures the lung tissue of test animals (young rats). This process of deterioration can be interpreted as an acceleration of aging.

Nitrogen dioxide plays an important role in the production of photochemical oxidation products which may cause eye irritation and, in severe cases, give rise to other complaints as well. A part of the irritating effect can be explained by the presence of formaldehyde and acrolein, as well as peroxyacetyl nitrate (PAN).

#### IV. Biological and medical criteria for air quality standards

The issuance of air quality criteria is a vital step in a programme designed to assist the authorities concerned in taking responsible technological, social, and political action to protect the public from the adverse effects of air pollution. The designation of tolerable concentrations of pollutants is thus the result of a multidisciplinary choice in a complex of criteria which are qualitatively and quantitatively dissimilar. But quite

apart from the importance one would like to attach to various types of criteria, one should realize that pollution is an evil that cannot be excused and which should be abated and prevented for its own sake.

Because a clean air policy depends in practice, on many more factors than just logic, common sense and good will, only relative, rather than absolute, criteria can be applied. For this very reason, however, one can never be too exhaustive in assessing whether measures to be taken do carry things far enough, for it is a feature of human nature in such problems to be content with little for the sake of convenience. In the matter of multiple choices and decision making, unidisciplinary criteria may serve as guidelines. Air quality criteria (in the American terminology) reflect the latest scientific knowledge of use in indicating the kind and extent of all identifiable effects on health and welfare which may be expected from the presence of an air polluting agent. Comprehensive evaluation and interpretation of criteria results in guides that indicate which effects are to be expected if exposure to pollutants exceeds definite concentrations and exposure times, and to what extent these effects will operate. Such guides are of fundamental importance, and yet all over the world people are engaged in study and evaluation of data that unfortunately are not yet appropriate to the subject in many instances.

There is as yet no agreement as to the interpretability of a number of qualitatively widely differing criteria, e.g. mortality and morbidity statistics versus Pavlovian methods and interpretations. Much depends on philosophy (pragmatism versus dogmatism), and guesswork in a field where knowledge is still lacking. Therefore only a very brief outline is given here, regarding the documents that describe the material in further detail.

There is general agreement that a single, 24-hour exposure of man, animals or plants to a concentration of  $\text{SO}_2$  in the order of  $200 \mu\text{g}/\text{m}^3$  ( $\sim 0.08$  ppm) will not induce any harmful effect.

In a comparable manner long term exposure to a mean  $\text{SO}_2$  concentration of  $75 \mu\text{g}/\text{m}^3$  ( $\sim 0.03$  ppm) will not result in any damage to man, animals or vegetation. Nevertheless it should be noted that even this relatively low level of  $\text{SO}_2$  causes a so-called "desert" of epiphytic lichens and mosses.

Higher concentrations and longer exposures will result in a situation where harmful effects become detectable. As regards man and animals such a "sensitivity threshold" may be around  $500$  to  $600 \mu\text{g}/\text{m}^3$  ( $\sim 0.2$  ppm) for a short term exposure (24 hours) and around  $150 \mu\text{g}/\text{m}^3$  ( $\sim 0.05$  ppm) as the mean  $\text{SO}_2$  concentration over a long period (years).

The transition from doses that are harmless to doses that increasingly lead to unwanted and deleterious effects is gradual and depends on the organism and the symptom under study, as well as on environmental conditions. But at exposures to  $2000 \mu\text{g}/\text{m}^3$  ( $\sim 0.8$  ppm) for 24 hours, and  $300 \mu\text{g}/\text{m}^3$  ( $\sim 0.1$  ppm) in the long term one has arrived at doses that induce deleterious effects which are unacceptable from the common sense point of view.

These figures apply to  $\text{SO}_2$  as an index of pollution by combustion products from the use of traditional fossil fuels.

For a full appreciation of the gradation of this transition from harmless to deleterious exposures, one should realize that a harmful influence may already be acting on single sensitive individuals at concentrations of pollutants which are considerably lower than the level at which exposures begin to have a statistically significant effect on large population groups.

If one really intends to promote clean air in order to prevent unpleasant effects occurring, one should consider the above mentioned figures concerning a hypothetical "sensitivity threshold" as purely tentative. They hardly give a true picture, and as such they should be appreciated simply as upper limits which in practice should never be reached and which should be rigorously underbid by a policy that intends to guarantee a harmless and comparatively healthy environment based on either the best available knowledge or on qualified guesses.

For further information on the subject the reader is referred to the publications listed in the bibliography.

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# CHAPTER 6. ENVIRONMENTAL EFFECTS SPECIFIC TO NUCLEAR POWER PRODUCTION

by J. A. G. Davids, J. A. Goedkoop and M. Muysken

## Summary

*The production of electric power from the fission of atomic nuclei is described as far as is necessary for an understanding of the environmental effects. Apart from the discharge of waste heat, common to all thermal power stations, these effects are all reducible to the exposure of man to ionizing radiation. There is broad international agreement on the safe limits for such exposure.*

*It is shown that the radiation exposure from the normal operation of nuclear power stations can be kept well within these limits. The fission products, which might be released due to malfunction of the nuclear reactor, present a potential hazard, but this can be reduced to virtually zero at acceptable cost. The same applies to the further handling of these fission products during nuclear fuel reprocessing and permanent storage.*

## I. Introduction

Bakker and Went [1], in their opening contribution, mentioned two methods of producing useful energy by reactions involving atomic nuclei: fission of heavy atoms and fusion of light atoms.

At present only the former process has been sufficiently developed to constitute a reliable source of energy for power stations and the propulsion of ships. The fission of the uranium or plutonium nucleus is induced by a neutron, and in turn produces further neutrons, enabling a chain reaction to occur. The process also produces fission fragments: atoms with unstable nuclei which eventually, via several intermediate stages, transform into stable atoms. Ionizing radiation is emitted in this radioactive decay process.

In order to obtain useful energy from the fission of atoms several steps are necessary, which are shown in the diagram, Figure 1. The uranium must first be mined and treated before being fabricated into fuel elements. During this part of the process the nuclear fuel emits only a small amount of radiation. In the next stage the fuel elements are placed in the core of the nuclear reactor. The heat generated by fission is carried away by a coolant which flows through the reactor core past the fuel elements. Part of this heat is transformed outside the reactor into useful energy.

At the same time within the reactor core a large amount of radioactive material is formed, primarily the fission products which remain embedded in the fuel elements and are removed from the reactor at the end of the fuel cycle. In addition, the neutrons induce radioactivity both in the coolant itself, and in the corrosion products from the piping system which are carried by the coolant stream. No materials at a distance further than a few metres from the core become radioactive during operation of the reactor. The spent fuel elements, after having been removed from the reactor core, are shipped to the fuel reprocessing plant where the remaining fissionable material, uranium and plutonium, is recovered. The

highly radioactive fission products are removed to a permanent storage site.

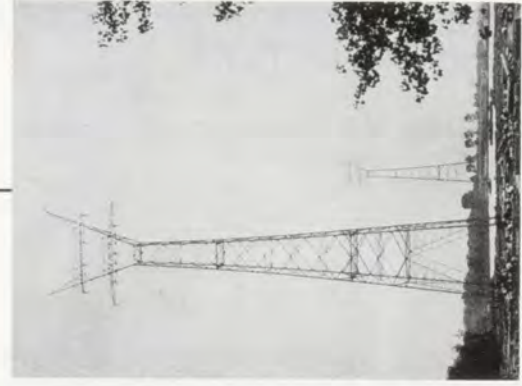
As will be discussed in the next section, the specific environmental effects of nuclear power are all reducible to the exposure of man to ionizing radiation. There are internationally agreed limits to this exposure, which are outlined in section III. The normal operation of nuclear power stations and of fuel reprocessing plants are discussed in sections IV and V respectively. Accidents with nuclear reactors form the subject of section VI.

## II. Environmental aspects

The production of nuclear power does not lead to the emission of chemical pollutants in the atmosphere such as smoke, soot, fly-ash and the gaseous oxides of sulphur, carbon and nitrogen which result from the combustion of fossil fuel.

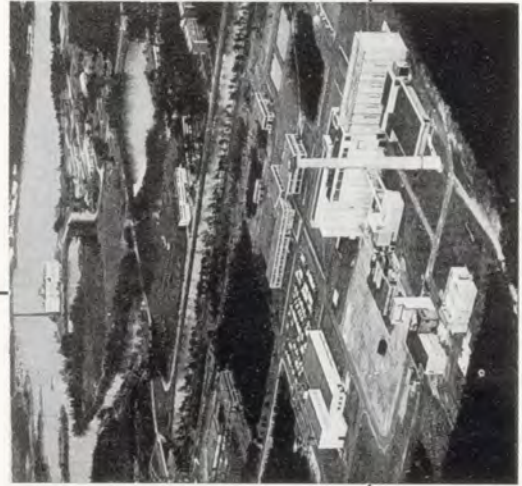
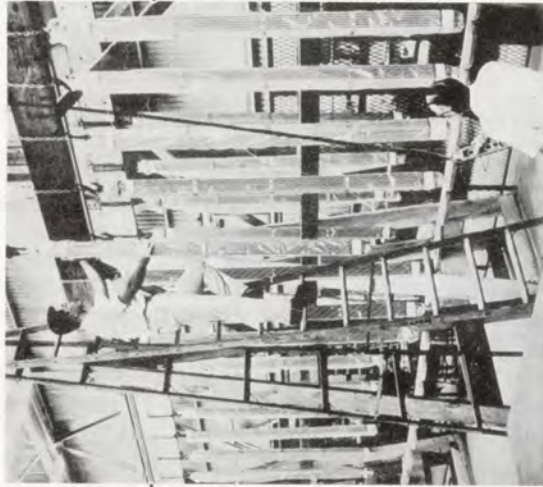
One environmental effect common to both fossil and nuclear fuels is the discharge of waste heat. According to the second law of thermodynamics only part of the heat energy can be converted into electrical energy, consequently the remainder has to be discharged into the environment. In those reactor plants in operation or being installed at the moment, the plant efficiency is about 32 % and does not differ appreciably from that of older fossil fuel plants. The remaining 68 % is completely rejected to the condenser cooling water. Modern fossil fuel plants have an overall plant efficiency approaching 40 %. Approximately 10 % of their combustion energy is dissipated directly into the atmosphere by means of the discharge of heated combustion products through the stack, and the remaining 50 % is transferred as waste heat to the condenser cooling water. Therefore the present type of nuclear plant needs about 1.7 times more condenser cooling capacity than a modern fossil fuel plant of the

NUCLEAR POWER PLANT



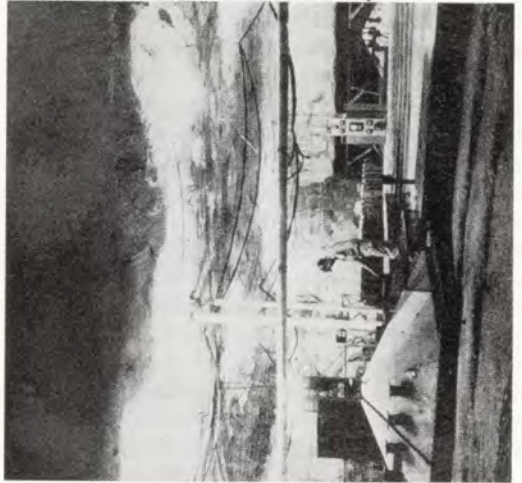
ELECTRICITY TRANSPORT

FUEL ELEMENT FABRICATION



FUEL REPROCESSING PLANT

URANIUM MINING AND ENRICHMENT



RADIOACTIVE WASTE STORAGE

Figure 1 - Electric power from uranium.



same power. It is expected that in future reactor types (see section IV) with a higher core temperature the efficiency of the steam cycle will be increased to between 39 and 43 %. For the methods used in dissipating condenser waste heat and for the thermal effects this has on the environment the reader may refer to the contributions of Keller [2] and Koolen [3] in this publication.

However, their one common factor is that they all contribute to the same environmental effect by increasing man's exposure to ionizing radiation to above the natural background level. Effects on animal and plant life are negligible in comparison.

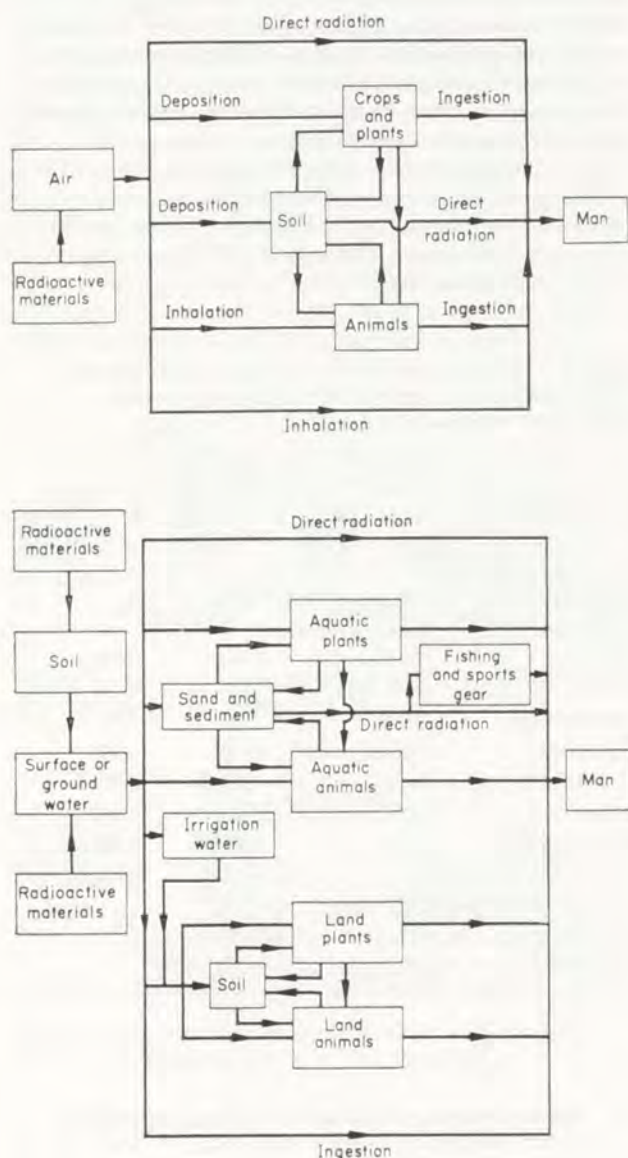


Figure 2 - Simplified pathways by which radioactive materials released in the environment may reach man (ICRP publication 7).

In this chapter we intend to evaluate the potential environmental hazard connected with the production of the large amounts of radioactive materials which result from nuclear power generation. The radioactive nuclides which are produced by fission and neutron activation in the reactor core are numerous and have widely differing half-lives. They represent many chemical elements and after their eventual release into the environment there are various and sometimes quite complicated routes by which they may reach man (Figure 2) [4].

### III. Radiation safety standards

The hazards to health of ionizing radiation were known long before the advent of the nuclear energy industry. Soon after the discoveries of X-rays and natural radioactive substances at the end of the last century it became apparent that unlimited external exposure to ionizing radiation led to acute damage in several organs. It later became evident that such exposure could also induce effects which only appeared after many years. The risk of internal exposure as a result of ingestion of radioactive substances was dramatically demonstrated after the First World War by the high death rate among luminous dial painters who had accumulated large body-burdens of radium and thorium in the course of their work. Finally, in 1927 Muller concluded from experiments with the banana fly *Drosophila* that exposure of the parents to X-rays caused genetic defects in their offspring. In many countries these findings led to regulations to prevent over-exposure and, in 1928, the international X-ray and Radium Protection Commission was established to provide guidance and co-ordination. The Commission, the name of which was changed in 1950 to International Commission on Radiological Protection (ICRP), recommends safety standards which are based on biological information accumulated and assessed by experts in the different fields.

The rapid growth of the nuclear energy industry has increased the scope of the Commission's task considerably: safety standards for neutron exposure were required, an assessment had to be made of the internal exposure resulting from inhalation and ingestion of the growing number of new radionuclides and the possibility of people being irradiated non-occupationally, due to release of radioactive nuclides into the environment, had to be considered. The most recent basic recommendations of ICRP were issued in 1966 [5]. They give dose limits for two groups of individuals:

- 1) adults exposed in the course of their work
  - 2) members of the public.
- The dose limits of the second group, which are one-tenth of those of the first group, are given in Table 1.

The ICRP has based these limits on the assumption that for late effects, notably the induction of malignant tumours, no threshold dose exists below which the risk is zero. An upper limit of risk has been estimated by a linear extrapolation of the dose effect relationship for high doses administered at high dose rates, down to the dose limits mentioned in Table 1. The ICRP estimated that the lifetime risk of cancer from a single whole-body exposure of 1 rem has an upper limit between  $10^{-5}$  and  $10^{-4}$ . The true risk figure is some-

**Table 1.** Dose limits for members of the public (ICRP 1966)

Organ or tissue	Dose limits *
gonads, red bone marrow (whole body uniformly irradiated)	0.5 rem in a year
skin, bone	3 rems in a year
thyroid (for age above 16 years)	3 rems in a year
thyroid (for age below 16 years)	1.5 rems in a year
hands and fore-arms, feet and ankles	7.5 rems in a year
other single organs	1.5 rems in a year

\* The rem is a measure that includes an estimate of the biological effectiveness of different types of ionizing radiation. For X-,  $\gamma$ - and  $\beta$ -rays 1 rem corresponds to an energy absorption of 100 ergs per gram of tissue. 1 millirem (mrem) =  $10^{-3}$  rem.

where between zero and the upper limit [6]. A more accurate direct determination is however beyond the scope of the available scientific methods.

If a large proportion of the population were exposed the consideration of hereditary effects would play a major role in setting the dose limit to the gonads. The recommendations of the geneticists as to dose limitation would be met in practice if, averaged over the population, the dose in the gonads during the first 30 years of life were limited to 5 rems. Again it is assumed that the hereditary effects are linearly related to the gonad dose, that no threshold dose exists, and that the dose effect relationship is independent of dose rate.

In view of the uncertainty of a threshold dose existing the ICRP recommends keeping exposure to ionizing radiation as low as practicable. Therefore the risks involved in its use have to be balanced either against the benefits obtained or against the risks inherent in alternative methods.

The ICRP dose limits are not intended to include doses from medical, diagnostic or therapeutic, exposures or doses from natural background irradiation. The latter is due to natural radioactive substances in the body (about 20 mrems/year), to cosmic rays (about 30 mrems/year at sea level) and to natural radioactive substances in the soil. This last component varies considerably depending on the soil type. It ranges from about 20 mrems/year over sedimentary rocks to about 170 mrems/year in granite districts. Above highly radioactive soils, in the Kerala State in India for instance, dose rates of up to 4.000 mrems per year have been measured.

On the other hand the ICRP dose limits apply not only to the production of nuclear power but also to a number of other human activities which may entail an increased exposure to ionizing radiation. For instance, flying at an altitude of 10 km gives an increased dose rate due to cosmic rays of about 0.5 mrem per hour. Watching colour television closely may expose one to soft X-rays. Radioactive substances are used for various non-medical purposes. Even the choice of construction materials for buildings can mean a

difference in indoor dose rate of about 20 mrems per year.

In planning the release of radionuclides into the environment the expected dose people receive from both external and internal irradiation has to be assessed. Internal exposure may result from ingestion of contaminated water and food or inhalation of contaminated air. Therefore the ICRP has issued figures derived from the dose limits [7, 8] laying down the maximum permissible intake, by either route, of many radionuclides. The maximum permissible intake of a single radionuclide is a complex function of its physical characteristics, such as type of emitted radiation and radioactive half-life, and its chemical form, which determines its pathway within the body. In Table 2 some figures have been assembled which serve to illustrate that, depending on the radionuclide, the maximum permissible intake (in microcuries) may differ by about a million.

**Table 2.** Maximum permissible continuous daily intake by either inhalation or ingestion for single radionuclides. (figures for members of the public)

Radionuclide	Critical organ <sup>1)</sup>	Ingestion $\mu$ Ci <sup>2)</sup>	Inhalation $\mu$ Ci
hydrogen-3 (tritium) as oxide	total body	8	3
ruthenium-106	gastro-intestinal tract	0.03	0.06
cesium-137	total body	0.03	0.04
strontium-89	bone	0.02	0.02
iodine-131	thyroid (adult)	0.005	0.006
strontium-90	bone	0.0008	0.0007
radium-226	bone	0.00003	0.00002
plutonium-239	bone	0.008	0.000001

<sup>1)</sup> Dose in this organ is limiting.

<sup>2)</sup> The curie (Ci) is the unit of radioactivity equal to  $3.7 \times 10^{10}$  disintegrations per second.  $1 \mu$ Ci =  $10^{-6}$  Ci.

#### IV. Nuclear power stations in normal operation

As mentioned in the introduction, the bulk of the radioactive materials formed by fission remain embedded in the fuel elements, which are usually bundles of metal tubes containing sintered oxide fuel. During fabrication the fuel elements are inspected very carefully in order to ensure that no leakage of radioactive materials from the fuel element will occur during operation of the reactor. However, in practice it is not always possible to achieve 100% leak-tightness. It must therefore be expected that the coolant will be slightly contaminated by fission products. A second source of contamination of the coolant is the activation, during the passage through the core, of impurities. These impurities are mainly the result of corrosion of the piping system through which the coolant passes.

The first nuclear reactors built in the US and the UK were cooled either by air, which was discharged through a stack, or by water, which was returned to the river. Nowadays the coolant circulates in a closed or almost closed circuit, and is either water, carbon dioxide or helium. For future reactors liquid metal (sodium) and molten salt mixtures (fluorides) are envisaged. In most cases the heat is transferred from the primary coolant to a steam cycle. Exceptions are the boiling water reactor and the gas-cooled reactor with direct cycle gas turbine. With liquid metal cooled reactors it is at present considered necessary to have an intermediate cycle between the coolant flowing through the reactor and the steam cycle.

Most reactors being built in the Netherlands, Belgium and Germany belong to one of the two types of water cooled reactors, either the pressurized water reactor (PWR), shown schematically in Figure 3, or the boiling water reactor (BWR), shown in Figure 4. As these reactors are the most prominent at present, and will continue to be so for at least the next decade, more detailed discussion will be restricted to them.

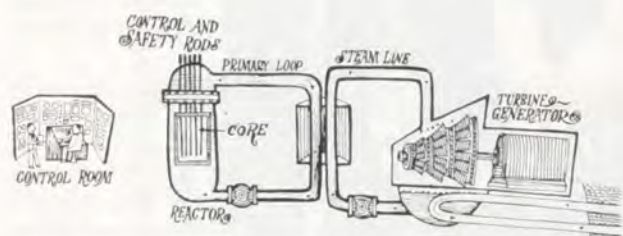


Figure 3 - Pressurised water reactor (PWR) power plant (from Atomic power safety, US AEC, DTI 64-62700).

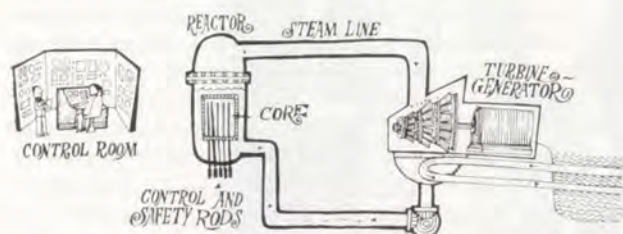


Figure 4 - Boiling water reactor (BWR) power plant (from Atomic power safety, US AEC, DTI 64-62700).

In the PWR the coolant system is completely closed. A certain part of the coolant is continuously bypassed through the purification system, consisting of filters and ion exchange beds, which trap all the circulating radioactive substances except those which are gaseous. The gases released from the reactor system are led through filters and charcoal beds in order to remove radioactive particles and iodine. The radioactive isotopes of noble gases can not be removed in this way. After a delay, in which most of the radioactivity decays, they are released to the environment through a stack at concentration levels below the limits set by the authorities and based on the standards discussed in section 3.

Used filters and ion exchange beds constitute the main body of solid radioactive waste from the power plant and are removed from time to time to a burial ground or other storage site.

Unavoidably, there is a certain amount of waste-water in which minor amounts of radioactive substances are dissolved. This low-level liquid radioactive waste is usually discharged into the cooling water stream from the condenser in order to dilute it to below the limits allowed for discharge to the environment.

In a modern PWR plant the low-level waste from the purification system will contain mainly tritium. This is formed by neutron absorption in the boron which is added to the primary coolant for additional control of the reactor.

The two different pathways for release or radioactive waste are shown schematically in Figure 5.

With the BWR system the primary coolant of the reactor is transformed to steam inside the reactor vessel, and is then led directly to the turbine. The steam next passes to the condenser, is condensed to feedwater, which is led back to the reactor vessel. A continuous extraction of vapour from the condenser is required in order to ensure sufficient vacuum. This results in higher release of radioactivity from the stack than is the case with PWR reactors. As an illustration, Table 3 gives annual release figures for a modern power station of each type:

These figures show that it is possible to operate both types of plants with radioactivity releases which are only a fraction of the official limits.

Table 3. Actual and permitted releases of radioactivity in curies per year

Location Type	San Onofre, Cal. USA 450 MW PWR [9]		Gundremmingen, W.-Germany 250 MW BWR [10]	
	actual	permitted	actual	permitted
through stack:				
noble and activation gases	260	567,000	17,500	1,920,000
iodine-131	0.0001 *)	0.8 *)	0.17	22
liquid effluent:				
fission and corrosion products	8	**)	2.4	14.4
tritium	3500	***)	24	4800

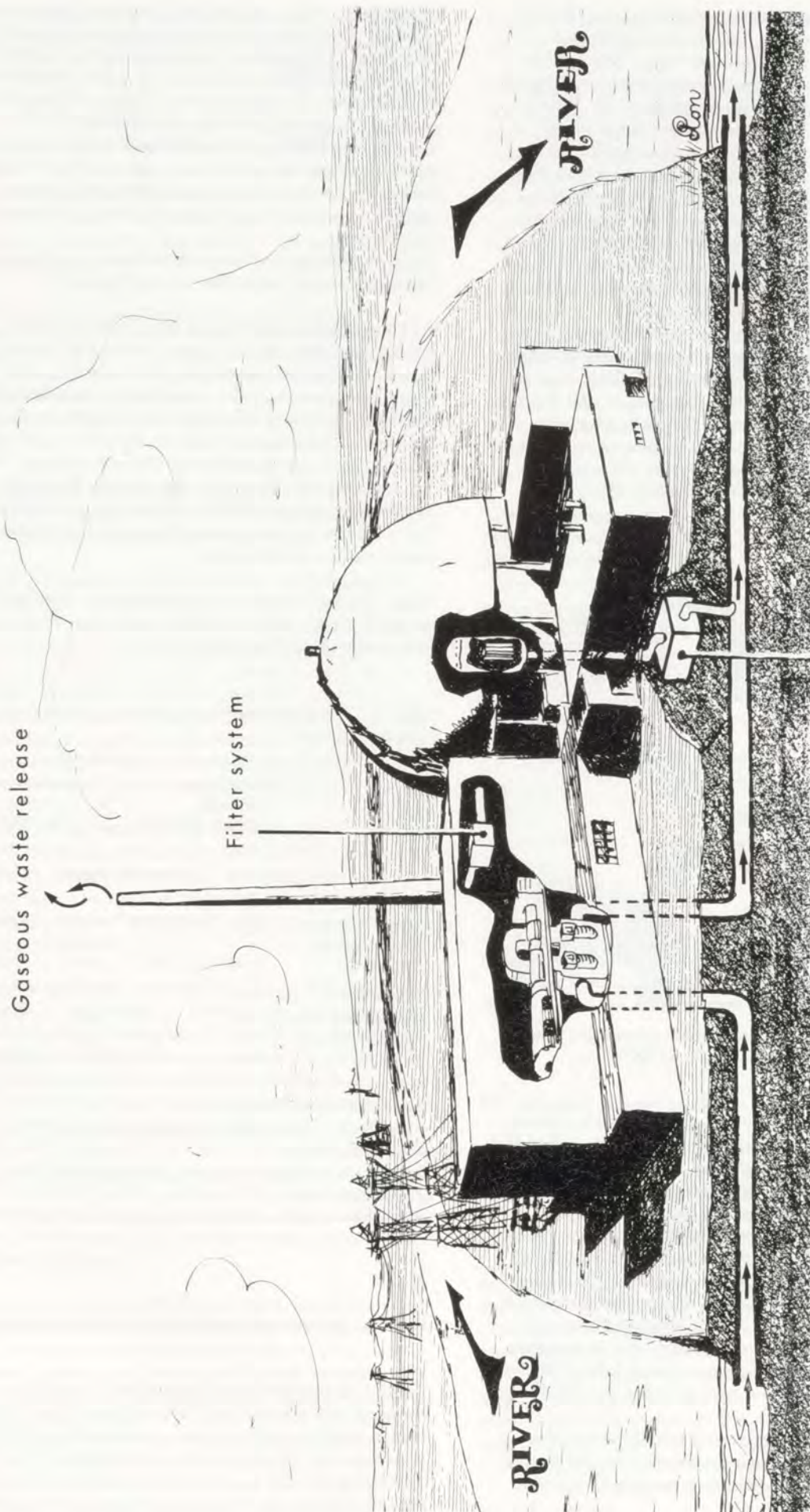
\*) includes radioactive particles

\*\* ) not given, actual average concentration was 14 % of permitted value

\*\*\* ) not given, actual average concentration was 0.2 % of permitted value

## V. Fuel reprocessing plants and waste storage

Spent fuel elements are reprocessed in order to separate the valuable uranium and plutonium from the fission products. All processes used today are of the aqueous type, which consists essentially of first dissolving the fuel in a nitric acid solution and extracting uranium and plutonium by means of an organic



Purification system releasing low-level liquid waste into the cooling water

Figure 5 - Release of radioactivity from a nuclear power station.

liquid. The aqueous solution of fission products, which is highly radioactive, is further concentrated by evaporation and stored in shielded stainless steel tanks which are cooled continuously and monitored for leaks. The whole process yields, apart from the high-active concentrated solution, a relatively large volume of liquid waste with a much lower radioactivity content in addition to gaseous radioactive waste, notably krypton-85 and tritium.

The permanent storage of the high-active waste has been a matter of concern for many years. The most promising solution seems to be to solidify the waste products and store them in caves in geological structures remote from ground water, preferably in salt deposits, which give, according to geologists, an absolute guarantee that the waste will not contaminate the biosphere. Two methods for solidification have been developed: melting the fission products together with  $\text{SiO}_2$  into a glassy substance, or calcination at high temperature resulting in a ceramic powder which is then packed in metal cylinders. In the USA new reprocessing plants will be equipped with a solidification unit, while, in Kansas, a permanent storage facility is being installed in a salt deposit.

A high purification of the medium and low-level liquid waste resulting from reprocessing is technically feasible. The extent to which it is put into practice depends, among other things, on the local disposal capacity. For instance, disposal of liquid radioactive waste into coastal seawater is used on a substantial scale in the English reprocessing plant at Windscale on the Irish Sea. The disposal capacity was first carefully assessed by dye dilution experiments and by considering all possible routes via which human exposure could result. The limiting factor appeared to be the concentration of the fission product ruthenium-106 by a red sea-weed *Porphyra*, which is harvested in the area and transported to Wales for consumption by a small number of people. It is estimated that the Windscale discharge might give, in a group of about 100 people, an exposure of the intestine up to 50 % of the ICRP dose limits [11]. Disposal of fission products in coastal water is also carried out in the French plant at Cap la Hague near Cherbourg. On the other hand the Eurochemic plant at Mol, and several plants in the USA, purify their liquid waste to a higher degree. The latter method produces of course more solid radioactive waste, which has to be disposed of in a selected burial ground.

Krypton-85 has the longest half-life (10.8 years) of the noble gas nuclides produced by fission. It easily passes the filter systems, which retain particles and iodine, and is discharged entirely into the atmosphere. The resulting exposure in the vicinity of reprocessing plants is at present negligible, but with the anticipated growth of nuclear power the estimated world-wide distribution by the year 2000 would give an appreciable dose, mainly in the skin, as a result of external exposure. It is therefore of interest that in the Oak Ridge National Laboratory rather a simple purification method has recently been developed in which krypton and xenon are absorbed in cooled freon. The krypton removal efficiency is claimed to be better than 99.9 %. This method will not only solve the future krypton-85

problem but will also be tested for its applicability in BWR plants in order to reduce the emission of short-lived radioactive noble gases [9].

The production of tritium (half-life 12.3 years) in the cooling medium and moderator of various reactor types has already been mentioned. Tritium is also formed in the fuel as a ternary fission product at a daily rate of about 50 mCi per MW electric power. With stainless steel, but not with zircaloy, some diffusion through the cladding of the element occurs. The tritium in the fuel is released in the reprocessing plant. With the reprocessing methods currently in use about 75—99 % of tritium present in the fuel appears as tritiated water (HTO) in the medium and low-level waste. It is released into the environment either as tritiated water vapour in the atmosphere, or directly in surface water. Because of the low radiotoxicity (see Table 2) of tritium as HTO the local capacity for disposal in surface water is considerable [12, 13].

## VI. Accidents in nuclear power stations and their consequences

Before a nuclear power station is built an extensive report on the safety of the station is drawn up and submitted to the authorities for approval. This safety report considers in detail the amounts of radioactivity which may be released to the environment during normal operation, as well as the amounts which would be released should various possible or hypothetical modes of plant malfunction occur, or should serious damage be done to parts of the plant.

As stated in section IV the fission products in the fuel constitute the main body of radioactivity in an operating reactor. A far smaller amount is present in the coolant of the primary system. Malfunctioning of the plant or damage to the primary coolant system such that only an enlarged leakage of primary coolant results, will not have serious consequences for the environment. The amounts of radioactivity involved are relatively small and the purification system and the filter system in the stack for trapping the gaseous radioactivity have sufficient capacity to cope with larger quantities than arise during normal operation. However, the release of fission products from the fuel must be prevented as completely as possible. There are several barriers incorporated in the reactor plant which prevent their release. In the first place a large part of the fission products is non-volatile, and thus remains in the fuel. The gaseous fission products will escape from the fuel, but are retained inside the cladding. Thus, as long as the fuel rods remain intact, no fission products will escape to the surroundings.

The next barrier is the primary coolant system. Then again the reactor and its primary coolant system are contained in a leak-tight building. Relatively small leakages from the primary cooling system and from the containment building must be accepted, but can be handled in such a way that release to the environment is less than the imposed limits.

A more serious situation can only occur if the cladding of the fuel rods fails disastrously. A conceivable cause for such a failure is overheating followed by melting of the cladding. This again could be a result of insufficient cooling of the fuel rods or of a sudden power surge.

The most serious case is a large rupture in the primary cooling system, leading to a loss of the coolant from the system. As this occurrence cannot be completely ruled out in the safety evaluation of the plant, the containment building is designed to cope with such a sudden rupture, followed by partial melting of the fuel cladding. An independent safety measure is the provision of an emergency cooling system, which comes into operation automatically to prevent melting of the cladding. Should the worst happen, and the emergency cooling system not operate fast enough to prevent melting of the cladding, a larger release of radioactivity to the surroundings than accepted for normal operation must be taken into account. However, such an extreme case has never yet occurred, and is only a hypothetical assumption in order to obtain design figures for the containment building and emergency cooling system.

The other possible cause for melting of the fuel rods, a sudden power surge, is even more unlikely than a sudden large rupture in the primary coolant system, at least with the present types of power reactors.

However, one such accident did happen in 1961 with the SL1, a prototype army package power reactor in the USA. This incident was presumably caused by jerking a control rod out of the core by hand, and cost the lives of three people. The amounts of radioactivity released to the environment, in this case the Idaho desert, were approximately:

iodine-131	80 curie
cesium-137	0.5 curie
strontium-90	0.1 curie

It must be added that the SL1 reactor was built in a corrugated iron shed; there was no containment building [14].

In the reactors of power stations now in use the neutron absorbing capacity of the individual control rods is kept so small that there would be no melt-down of the fuel if one rod were suddenly withdrawn from the core. Furthermore, the control systems shut the reactor down if the power or the rate of power increase exceed preset limits. Lastly there is a self-limiting mechanism, which also operated in the case of the SL1 incident, and which reduces the power level after a rise of temperature of the fuel, or the coolant, or both. The discussion of this inherent safety feature would lead outside the context of this paper.

More radioactivity was released in the accident at Windscale with an early reactor which was cooled by air. The air was released from the stack after passing through the core. Thus there was no closed primary coolant system nor a containment building. In October 1957 part of the fuel elements in this reactor melted. It has been estimated that the following amounts of radioactivity were released from the stack:

iodine-131	20,000 curie
tellurium-132	12,000 curie

cesium-137	600 curie
strontium-89	80 curie
strontium-90	2 curie.

The spread of radioactivity could be measured with highly sensitive instruments as far away as Frankfurt in Germany. However, the only practical measure which was necessary to protect the population was to prohibit the use of milk in an area of about 200 square miles for about 25 days in the greater part of this area, and for 44 days in the most highly contaminated region. Fourteen members of the staff received a dose of over 3 rems in the period of 13 weeks, the highest dose being 4.7 rems. Some of the population in the downwind sector received a dose in the thyroid as a consequence of the iodine, the highest recorded being 16 rems in a child. An independent committee set up by the Medical Research Council concluded "that it was in the highest degree unlikely that any harm had been done to the health of anybody whether a worker in the Windscale plant or a member of the general public" [15].

## VII. Conclusion

The first manifestations of nuclear energy in the form of atomic weapons were so awe-inspiring that its civil applications have been surrounded with great care for public health. As a result, it can be said with confidence that the normal operation of nuclear power plants presents no environmental problem apart from the heat release which is common to all thermal power stations. Care must be taken, however, to contain the large amounts of radioactive fission products, within the reactor, even in the case of a malfunction, and afterwards during reprocessing and long-term storage. Technically this is feasible, and at acceptable costs.

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