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Methods of combatting pollution
resulting from chemical spills.

September 1981

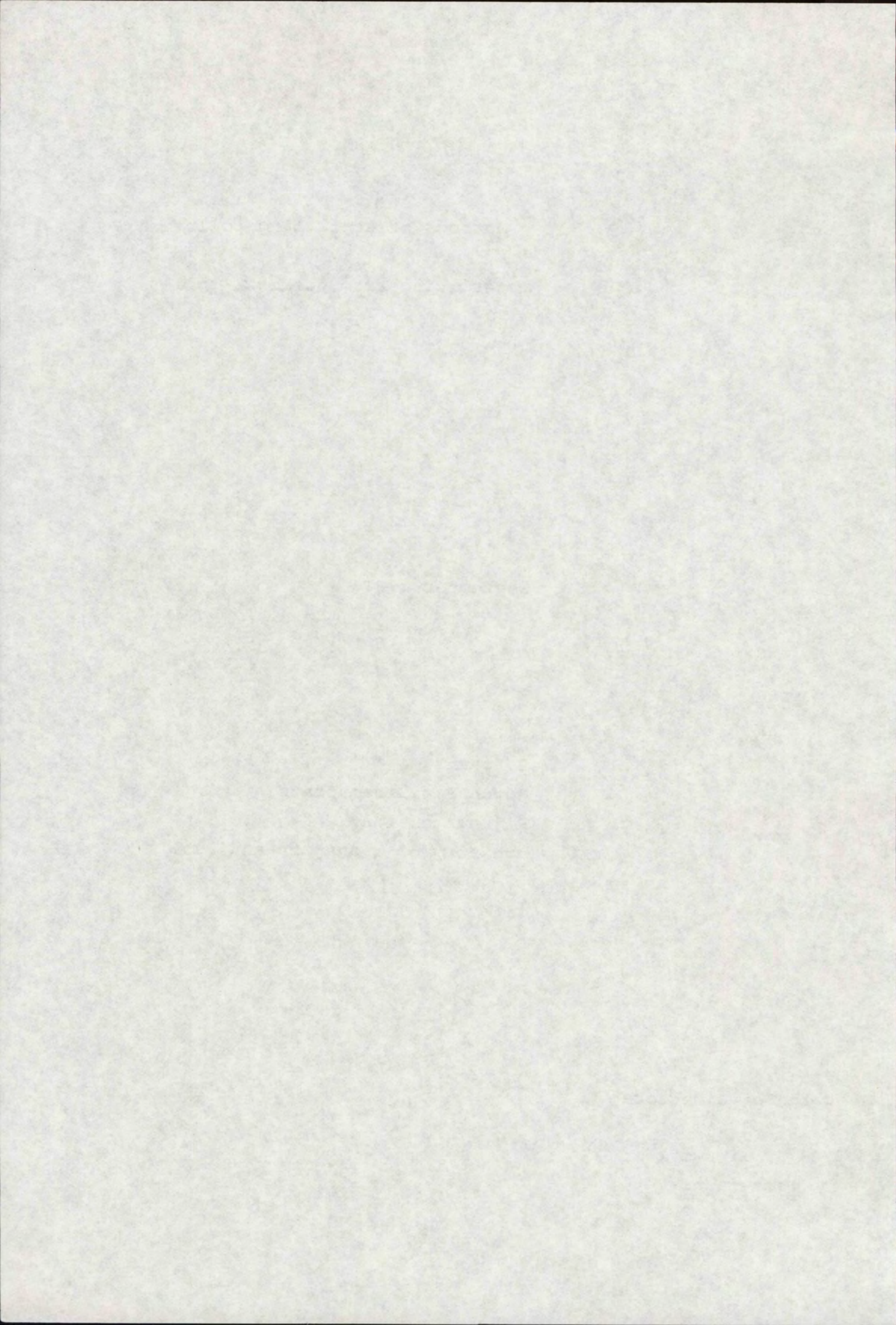
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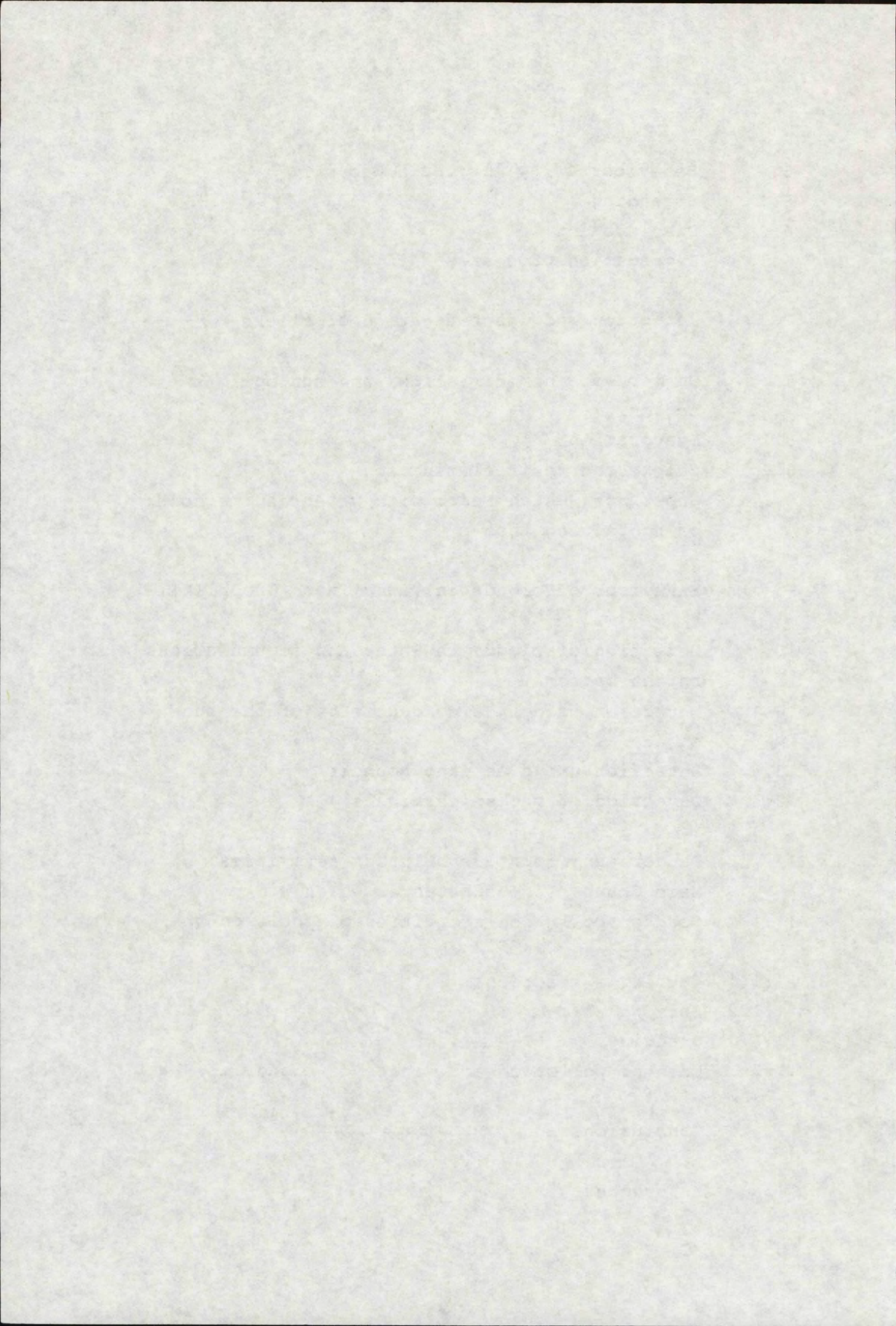
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Summary

Chances of calamities with bulk transport of chemicals have grown considerably during the last decade, because of the increased sea transport. The report deals with the question how to abate the escaped substances in the best possible way.

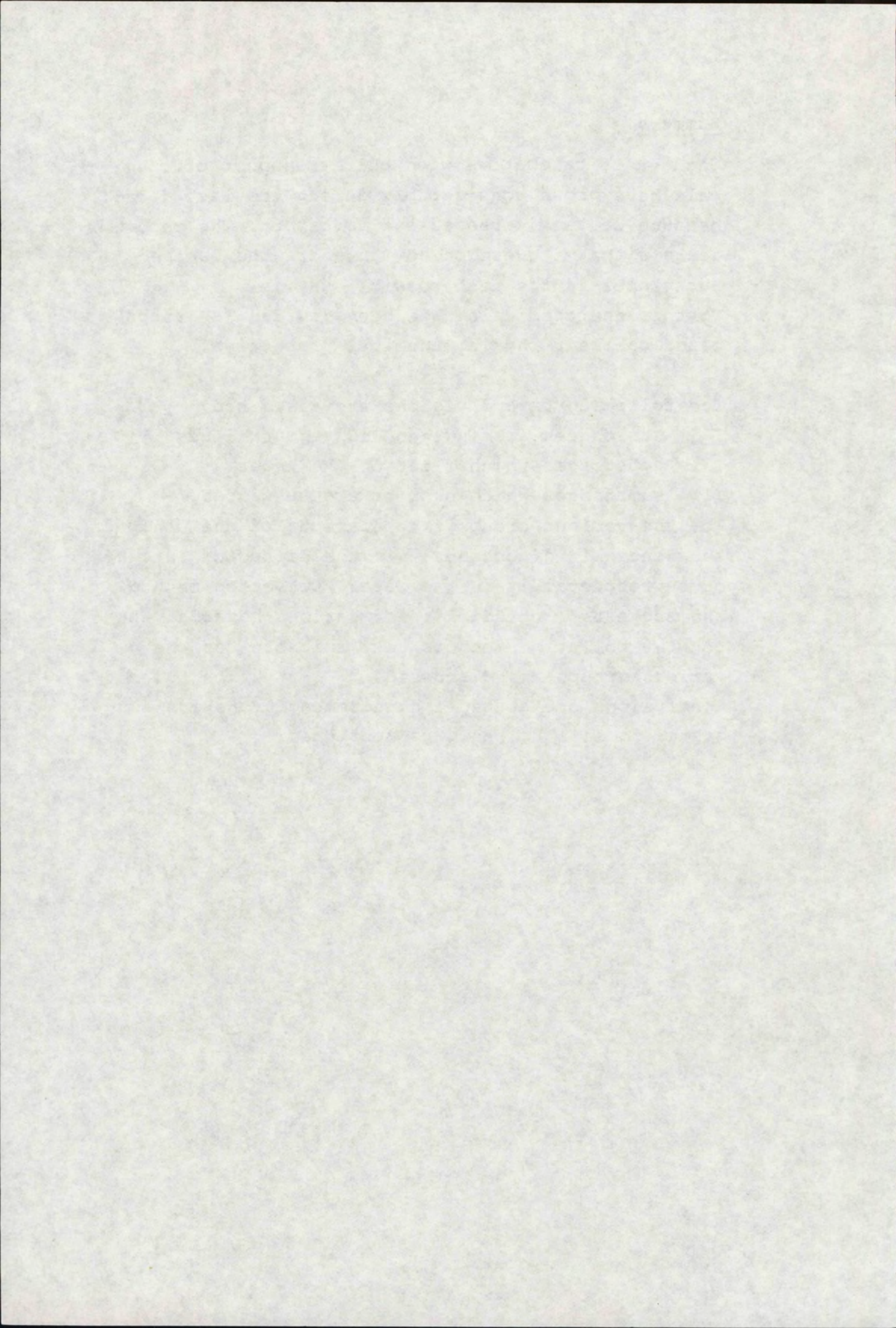
To this end chemicals have been divided in groups based on their physico chemical properties.

The following main divisions are discerned:

- I substances forming gas and vapour clouds
- II substances which float on the water
- III substances which sink or are suspended.

For the various groups the behaviour of the escaped substances is discussed, e.i. the diffusion in air; or on respectively in the water. Detection methods are suggested including their various hazards. The counter pollution methods best suitable for the various groups are discussed.

Conclusions are stated and recommendations are suggested to fill up the gaps mentioned.



1. Introduction

The constant increase in demand for chemical products has been accompanied by considerable growth in transport by water, with large quantities of chemicals frequently being moved in bulk. This has also increased the probability of accidents, resulting in the escape of chemicals. Such accidents may give rise to the danger of explosions or fire or of damage caused by the toxic properties of the escaping substances. This report discusses the best means of dealing with substances that have escaped.

Most substances transported in bulk by water are liquids, the majority being crude oil and oil products. Some solids are converted to liquid form for transport purposes, and some gases are compressed to form liquids before they are transported.

Where pollution occurs, a knowledge of the physical and chemical properties of the substance concerned and the dangers inherent in its escape is important. Such information can be obtained from various manuals on chemicals.

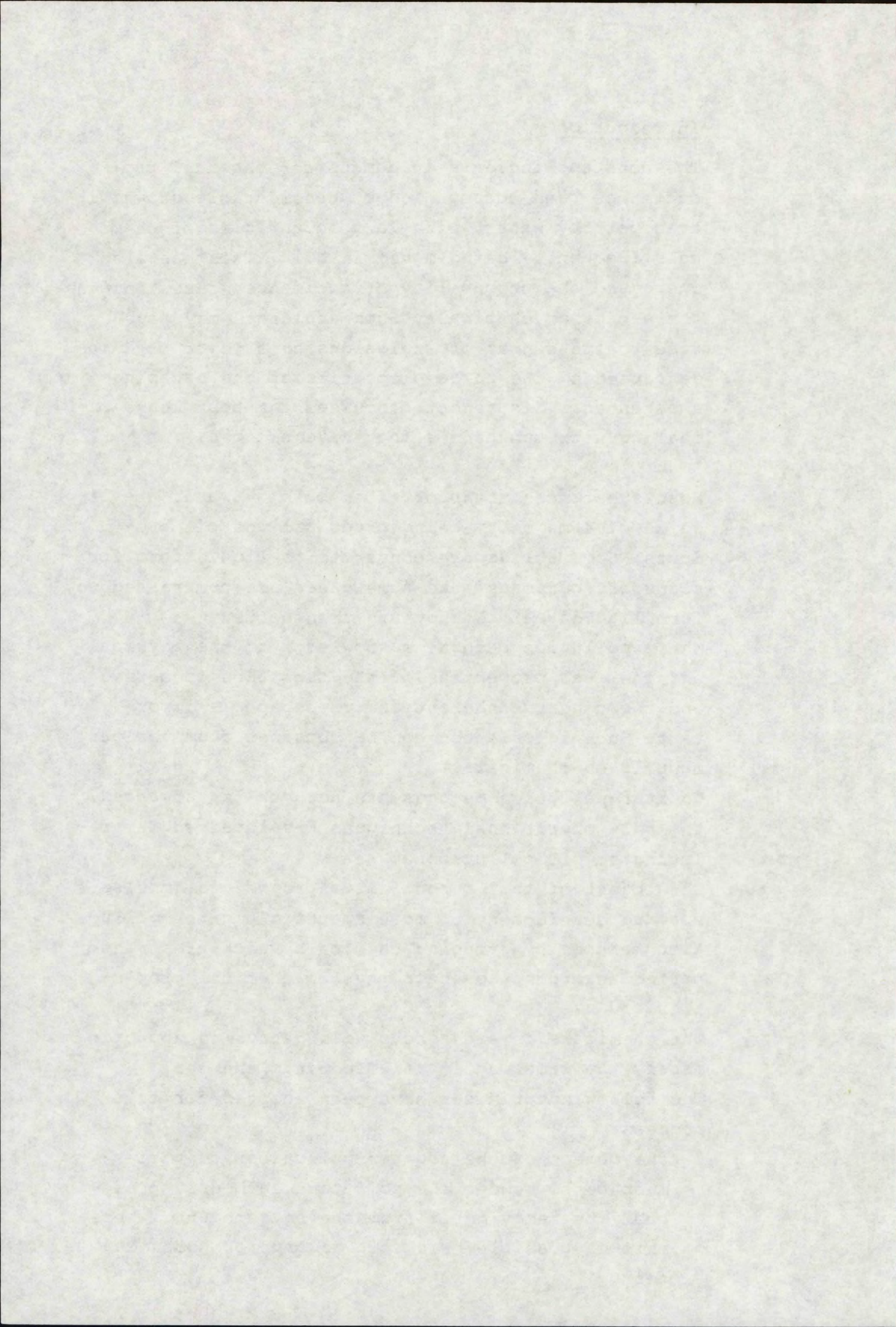
Counter-pollution methods are not yet far advanced, the only operational techniques developed so far relating to oil pollution at sea.

The object of this report is to provide an impulse for the development of more specific counter-pollution methods by grouping chemicals which are transported according to their physico-chemical properties.

The chemicals in each group will behave in approximately the same way if released into the sea.

The following premises have been adopted for this process:

- . the object of the counter-pollution activities must be to render the pollutant harmless, preferably by removing it from the environment, where this is possible, with due regard for human safety.



- . The counter-pollution methods, equipment, etc. developed should as far as possible dovetail with existing methods, equipment, etc.
- . Wherever possible, the attempt must be made to develop uniform methods. A specific method for a given chemical may be more effective, but the enormous logistical and financial implications do not generally justify this approach.

This report is not concerned with radio-active substances or with composite substances such as crude oil.

What happens

Where chemicals escape into the water in a disaster, they spread over various environmental compartments as different spread phenomena occur:

- . primary spread phenomena

Phenomena resulting in the substance tending to accumulate in the compartment with which it has the greatest affinity in view of its properties, e.g. state of aggregation, density compared with air or water, reaction with water, etc.

The compartments may be air, water surface, water and the surface of the seabed.

The mechanisms occurring here are: rising, evaporation, floating, reaction with water and sinking. These mechanisms in fact determine the location of the pollutant with the passage of time. Thus the chemicals can be divided into three main groups:

- I substances which form gas and vapour clouds
- II substances which continue to float on the water
- III substances which sink or remain suspended.

This division will be discussed in greater detail in Chapter 2.

. Secondary spread phenomena

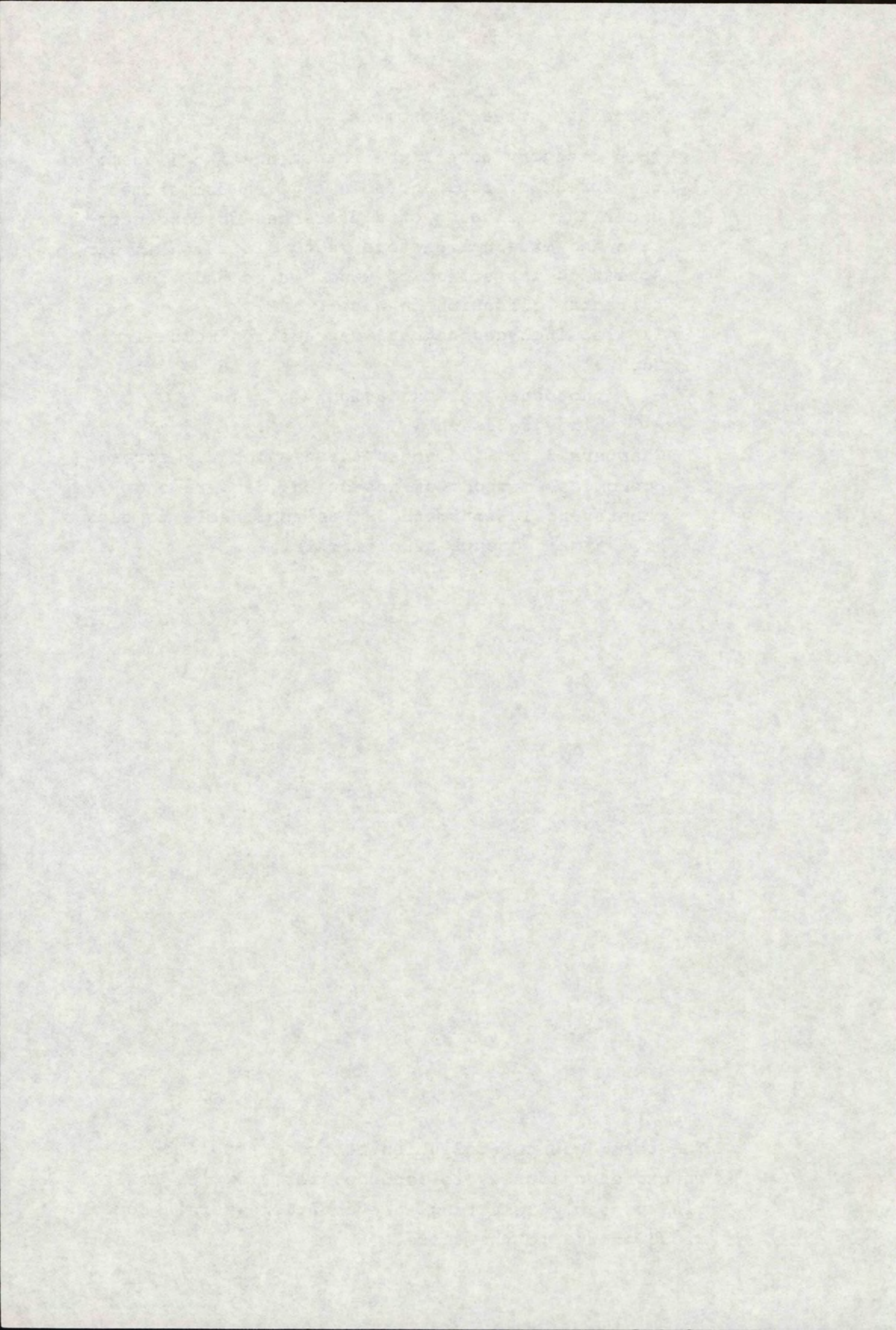
This category covers the phenomena that lead to the spread of substances in a given compartment under the influence of differences in concentration and external factors, e.g. diffusion in air, spreading, the effect of wind, waves and tidal currents, diffusion in water.

It also includes natural degradation mechanisms such as:

- photochemical oxidation
- biodegradation.

Chapters 3 to 11 discuss these secondary spread phenomena, methods of detection, dangers and counter-pollution methods* as applicable to each of the main groups of chemicals.

* The term "counter-pollution methods" should be interpreted loosely to include, for example, activities possibly resulting in evacuation where a toxic cloud drifts to the shore.



2. Grouping chemicals

2.1 Introduction

As explained in Chapter 1, the following main division of chemicals has been chosen:

- Main Group I : substances which form gas and vapour clouds
- Main Group II : substances which continue to float on the water
- Main Group III : substances which sink or remain suspended.

Figure 1 provides a more detailed picture of this division. It is so arranged that the criteria of greatest importance for spread are at the top.

The criteria used in this division are as follows:

- state of aggregation at 5 to 15°C: the temperature of the seawater off the Dutch coast varies from 5°C in winter to 15°C in summer. In hot summers the latter temperature may be somewhat higher.
- Density compared with sea water: the density of sea water is $\pm 1025 \text{ kg/m}^3$ at a temperature of 5 to 15°C.
- Density compared with air: the density of air has been taken as 1.
- Partial vapour pressure: 150 mm Hg at 5 to 15°C. Calculations (see Appendix I, for example) have shown that chemicals floating on water and having a partial vapour pressure of 150 mm Hg or more evaporate at a rate of many tonnes per hour.

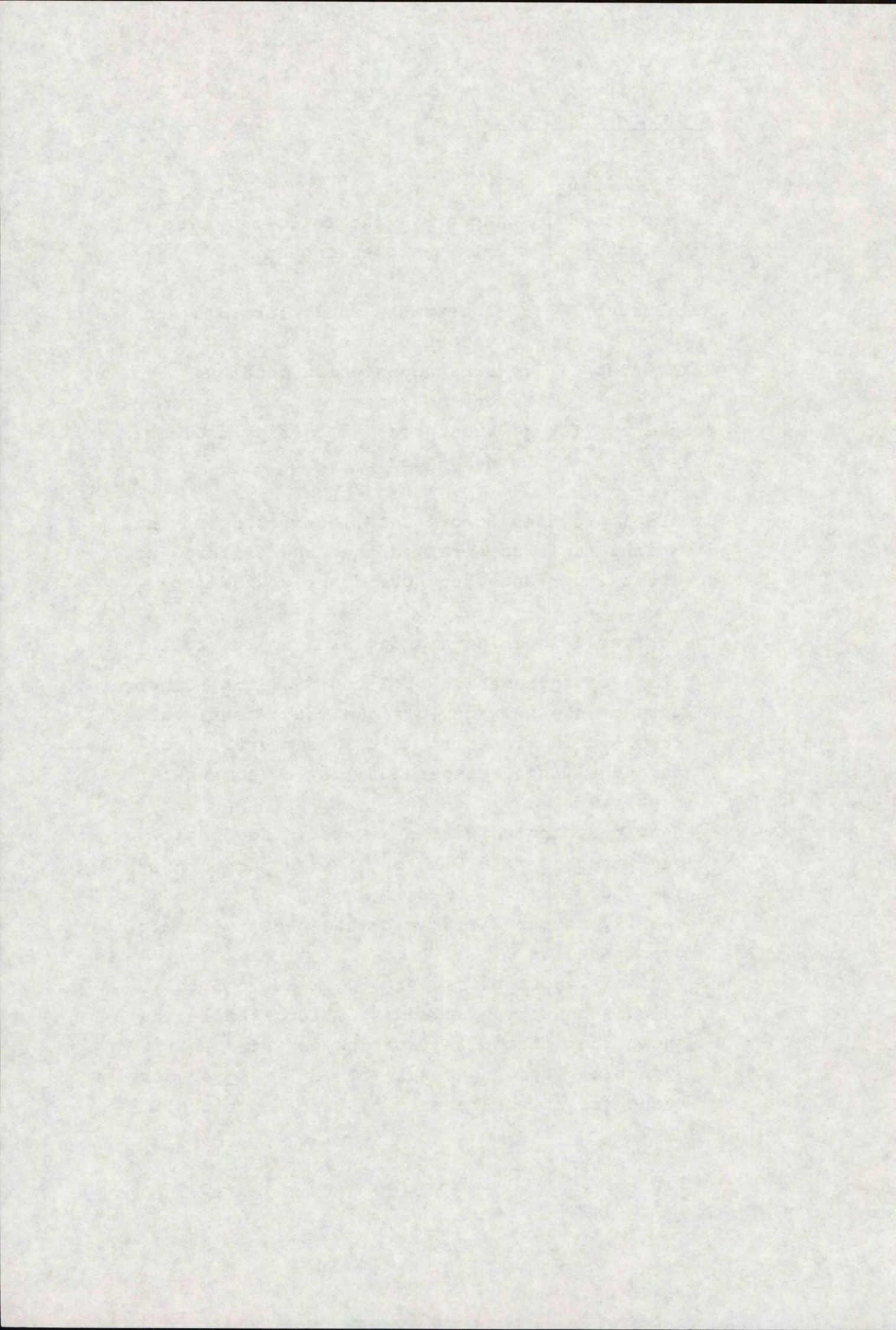
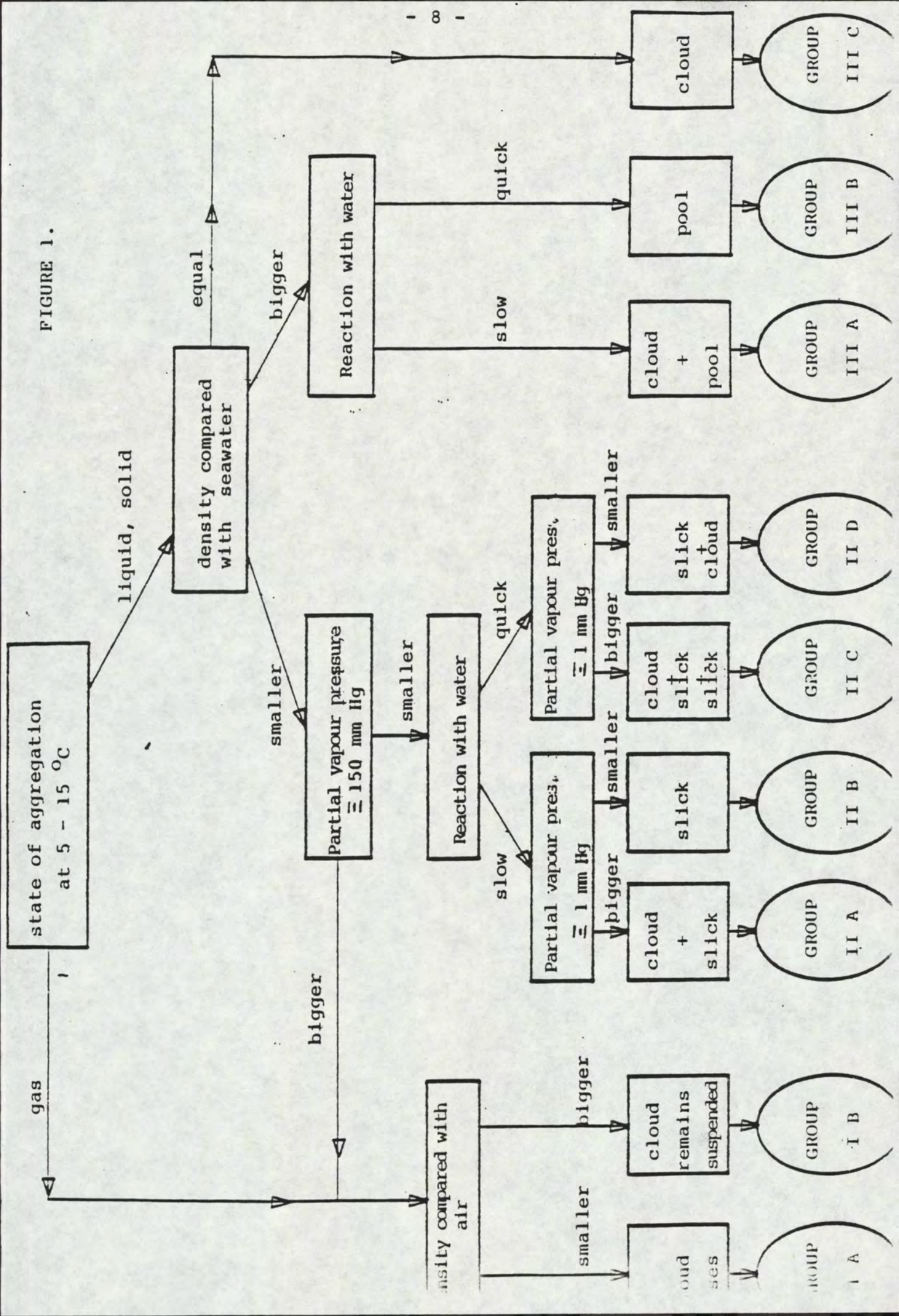
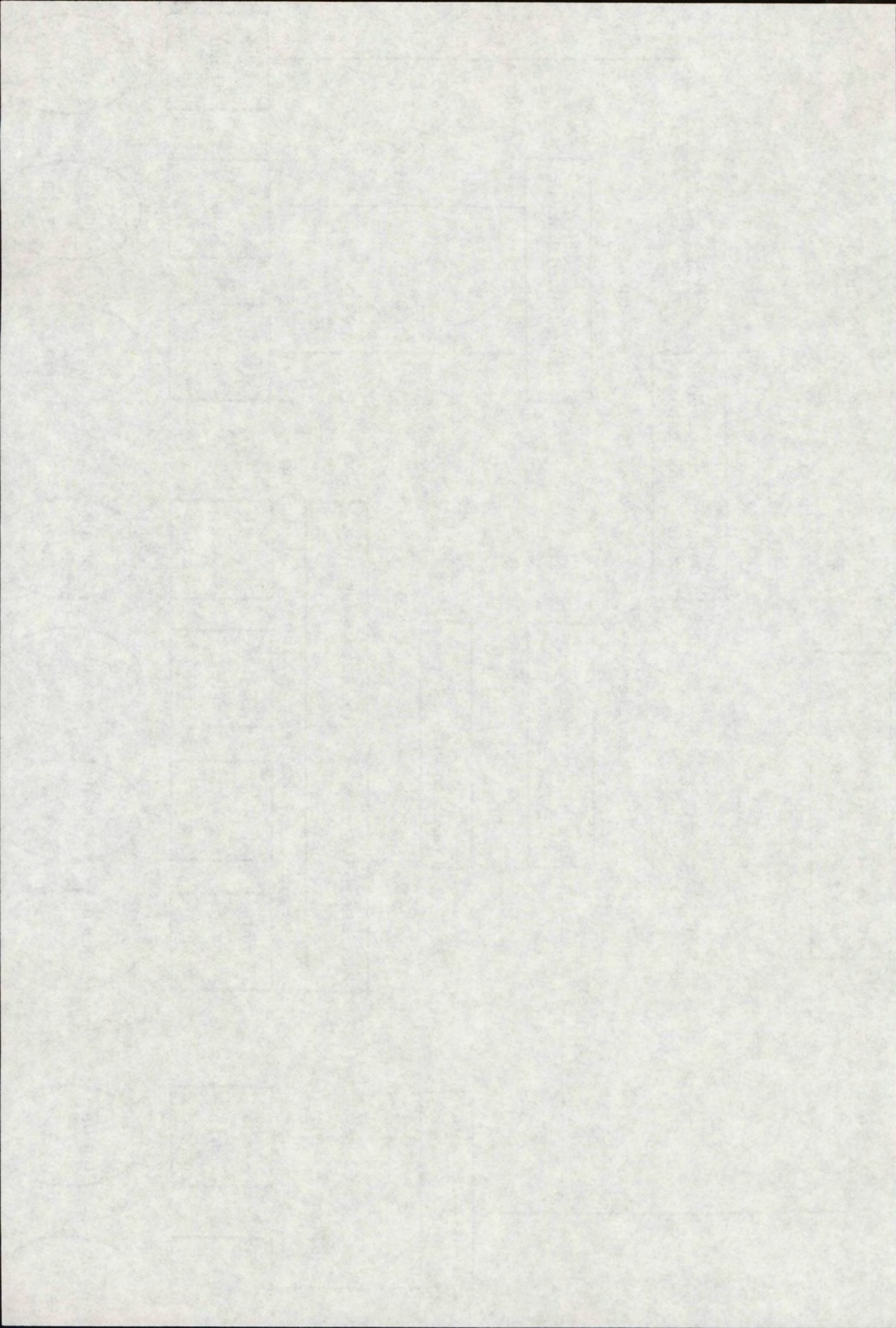


FIGURE 1.





- Reaction with water.

This covers both physical and chemical reactions with water and includes such processes as dissolution decomposition and hydrolysis. One of these processes will always occur. The question is, however, whether a process of this nature can bring about a significant change the determining factor being the reactionrate.

- Partial vapour pressure: 1 mm Hg.

By bringing about the division the partial vapour pressure for about twohundred much transported chemicals was obtained. As far as figures were known, values about 1 mm Hg appeared to be the lowest values. Therefore the evaporation of chemicals with lower values than 1 mm Hg at 5-15°C is considered to be negligible.

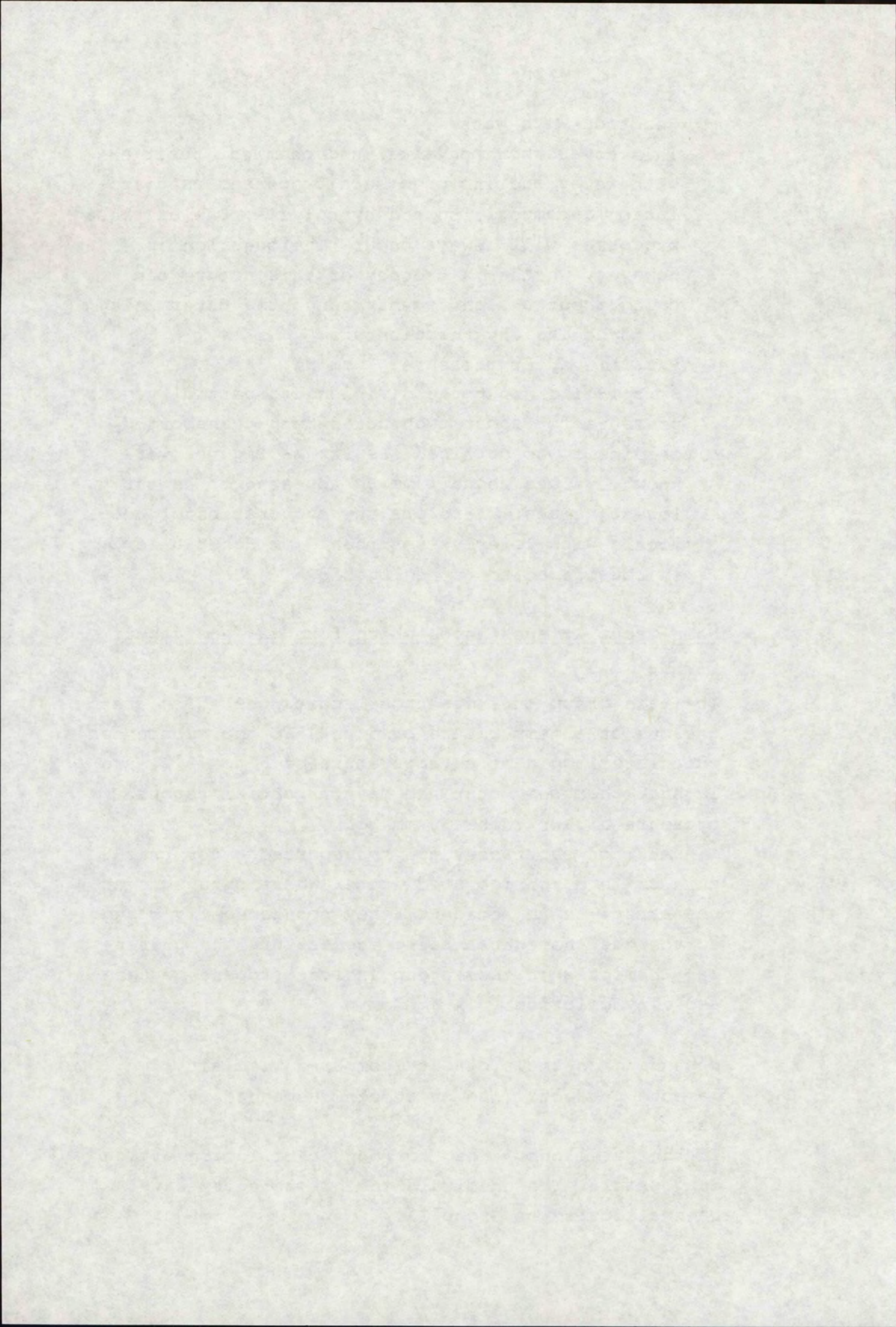
2.2 Main Group I: substances which form gas and vapour clouds

The main group includes those substances which are gaseous at a temperature of 5 to 15°C and substances which are liquid at a temperature of 5 to 15°C, are lighter than sea water and have a partial vapour pressure higher than 150 mm Hg.

A number of substances are transported under pressure or in a refrigerated state. Where such substances escape in an accident, they spontaneously change to the gas phase at ambient temperature and pressure. Chemicals in this group include propane, butane and vinylchloride.

Depending on their density compared with air, gaseous products rise or remain suspended over the water.

If the gas cloud rises, no counter-pollution action is possible. The chemicals in this category have been allocated to Group IA.



If the cloud remains suspended, caution is required. The explosion limits and gas concentration determine whether a gas cloud is explosive. Poisonous gas concentrations which, although not explosive, are dangerous for human beings and animals because of their toxicity may also occur. Although counter-pollution activities are not always possible, some appropriate action must be taken.

This group is known as IB.

2.3 Main Group II: substances which float on the water

All solid and liquid substances having a density lower than that of sea water will float on the water if they escape.

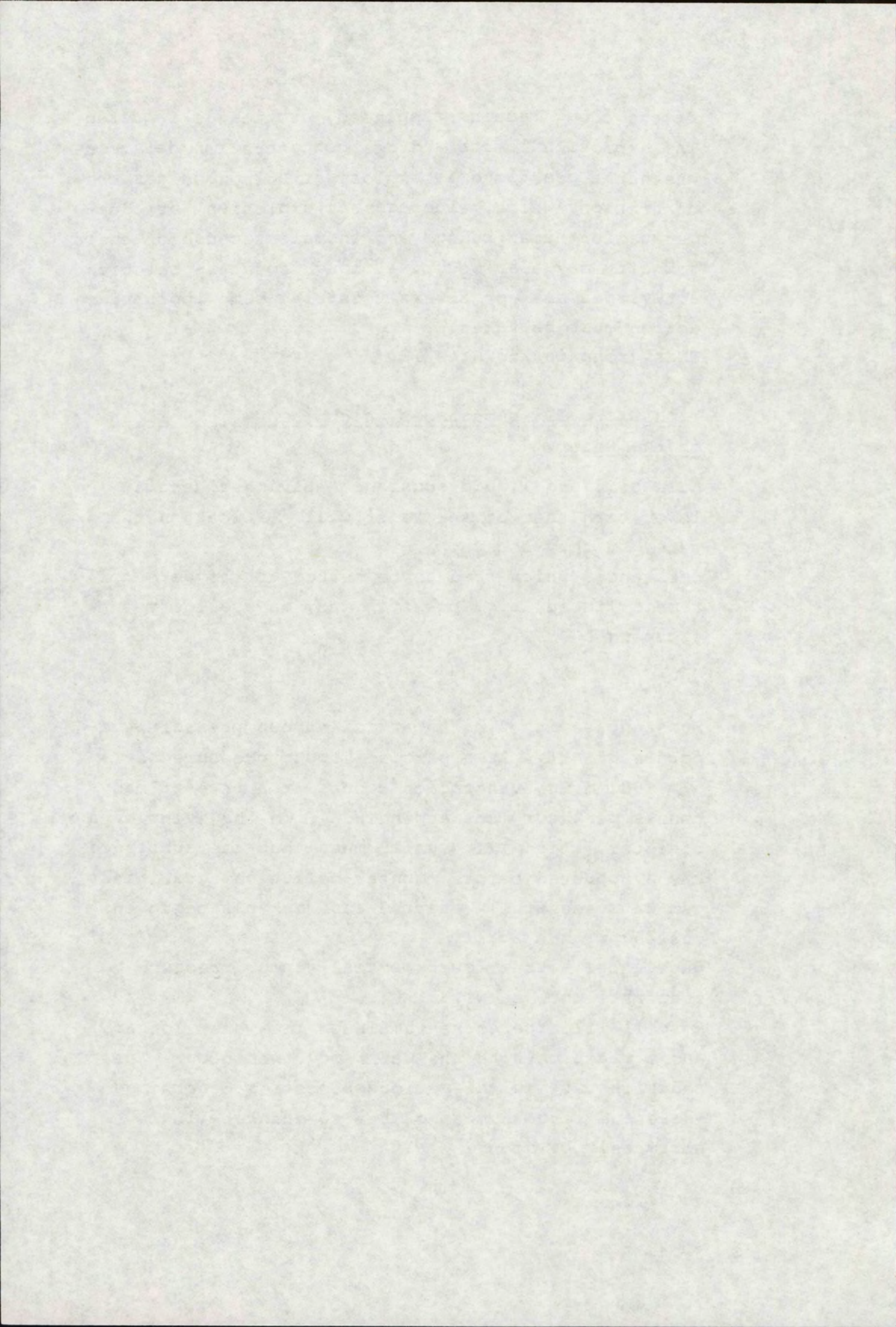
Substances which need to be heated if they are to remain liquid, e.g. paraffin wax, may solidify on escaping.

Substances with a high partial vapour pressure evaporate quickly. At a partial vapour pressure of

> 150 mm Hg evaporation occurs at a rate of many tonnes per hour (see Appendix I). In the event of a disaster, this will usually mean that the substance has evaporated before counter-pollution activities can be successfully started and work has begun on dealing with a spill.

Substances with a lower partial vapour pressure evaporate more slowly.

A spill will therefore remain on the water longer, and a reaction with the water may then occur. The reaction rate in the various processes determines where the largest mass of the substance will ultimately be found.



Main Group II can thus be divided into the following sub-groups:

- IIA : substances which float on water and form a slick over which a gas cloud is suspended, their reaction with water being negligible;
- IIB : substances which float on water and simply form a slick, evaporation and reaction with water being negligible;
- IIC : substances which float on water and form a slick over which a gas cloud is suspended, a reaction with water also occurring;
- IID : substances which float on water, form a slick and react with water, virtually no evaporation occurring.

2.4 Main Group III: substances which sink or remain suspended

All solid and liquid substances with a density which is greater than that of sea water will sink towards the bottom.

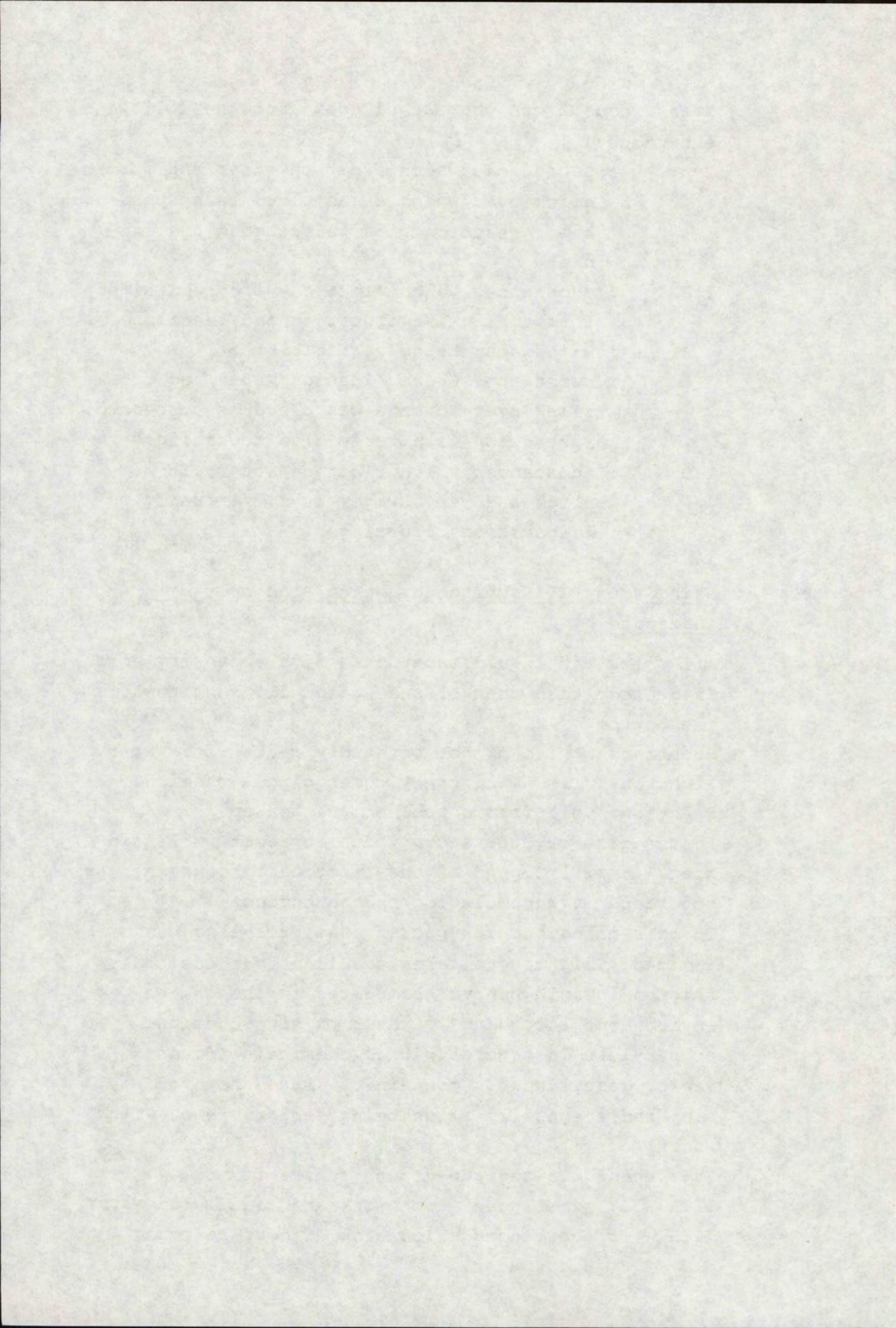
Substances which do not or hardly react with water, either by dissolving or by undergoing a chemical reaction, will form a pool on the bottom.

In the case of substances which do react while sinking, it will depend of the reaction rate whether or not there is accumulation on the bottom.

In this maingroup the packed chemicals also can be divided. This report takes the line that chemicals shipped in bulk behave themselves in the marine environment according to their physico-chemical properties. In general packed chemicals (drums, sacks, gas cylinders, containers, etc.) however will sink and eventually after being damaged react with water.

Thus the following sub-groups can be formed:

- IIIA : substances which sink and react with water
- IIIB : substances which sink without reacting with water.



In addition there is a small group of chemicals which, in view of the division made in Figure 1, should in fact form a separate main group: substances which remain suspended.

In view of the limited size of this group, however, they have not been allocated to a separate group. The best-known chemicals of this group are aniline and caprolactam.

IIIC : substances which remain suspended since their density is similar to that of sea water.

2.5 Grouping chemicals in terms of counter-pollution methods

It was decided to divide chemicals into sub-groups as in sections 2.2 to 2.4 in terms of possible counter-pollution activities. The arrangement is therefore clearly "action-orientated". Such action should be geared to rendering harmless as much of the pollutant as possible.

The division into groups is shown in another way in Figure 2.

Table 1 also lists the chemicals handled in the Port of Rotterdam in the order of their categories.

The list is based on 1979 figures. It is thus possible to estimate the probability of a disaster involving a given chemical, although this is not done in this report. In this connection, it is also important to know what quantity of chemicals is located at any given part of a chemical carrier. This aspect is currently being investigated and will form the subject of a separate report.

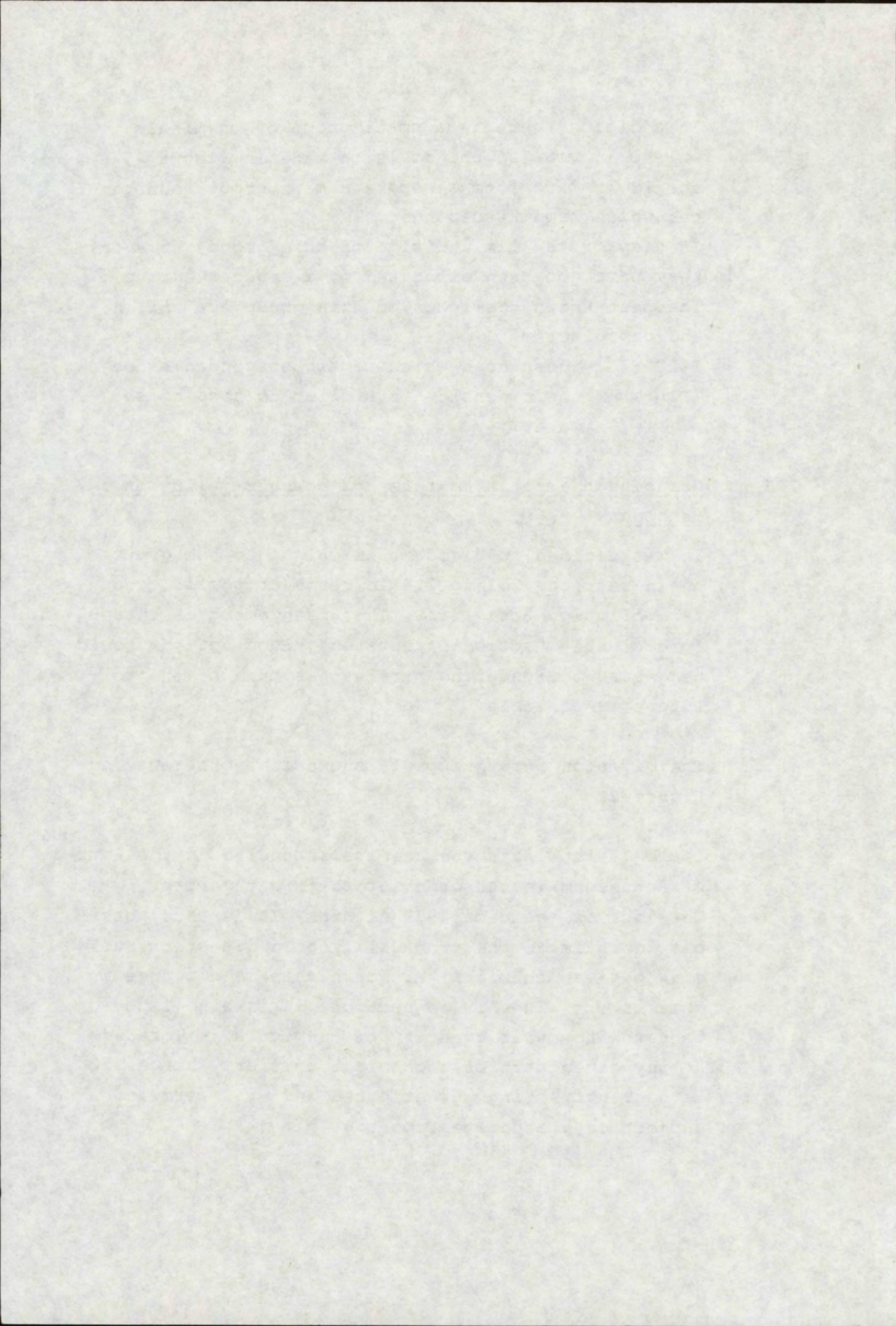


Figure 2.

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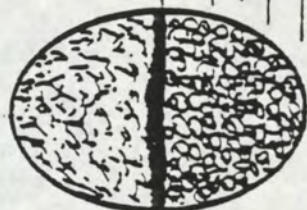
Group I B Group II A



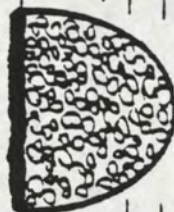
Group II B



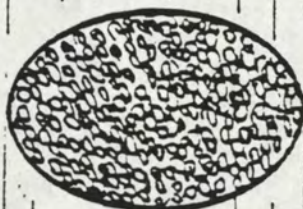
Group II C



Group II D



water surface



Group III C

Group III A



Group III

bottom

Figure 2

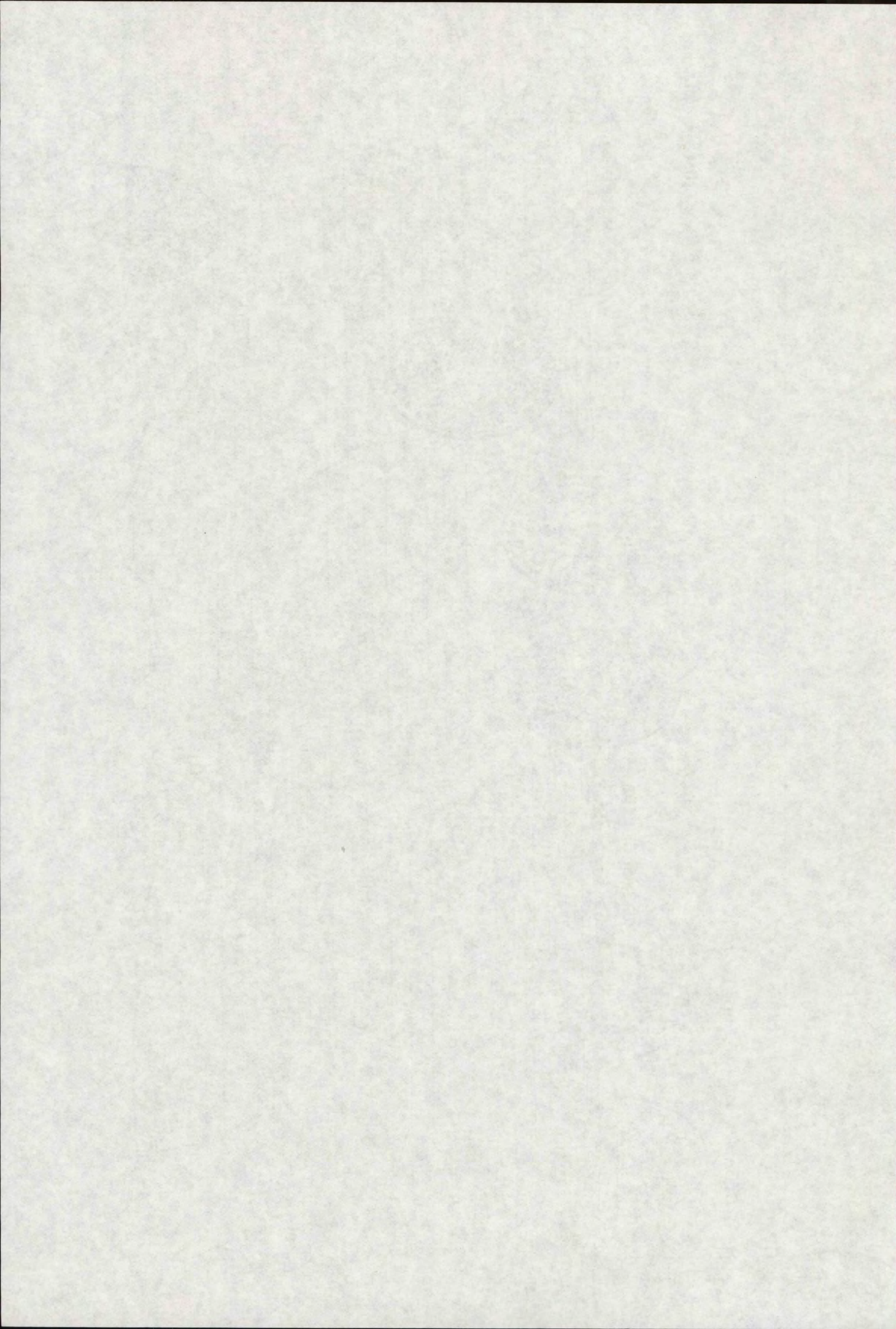
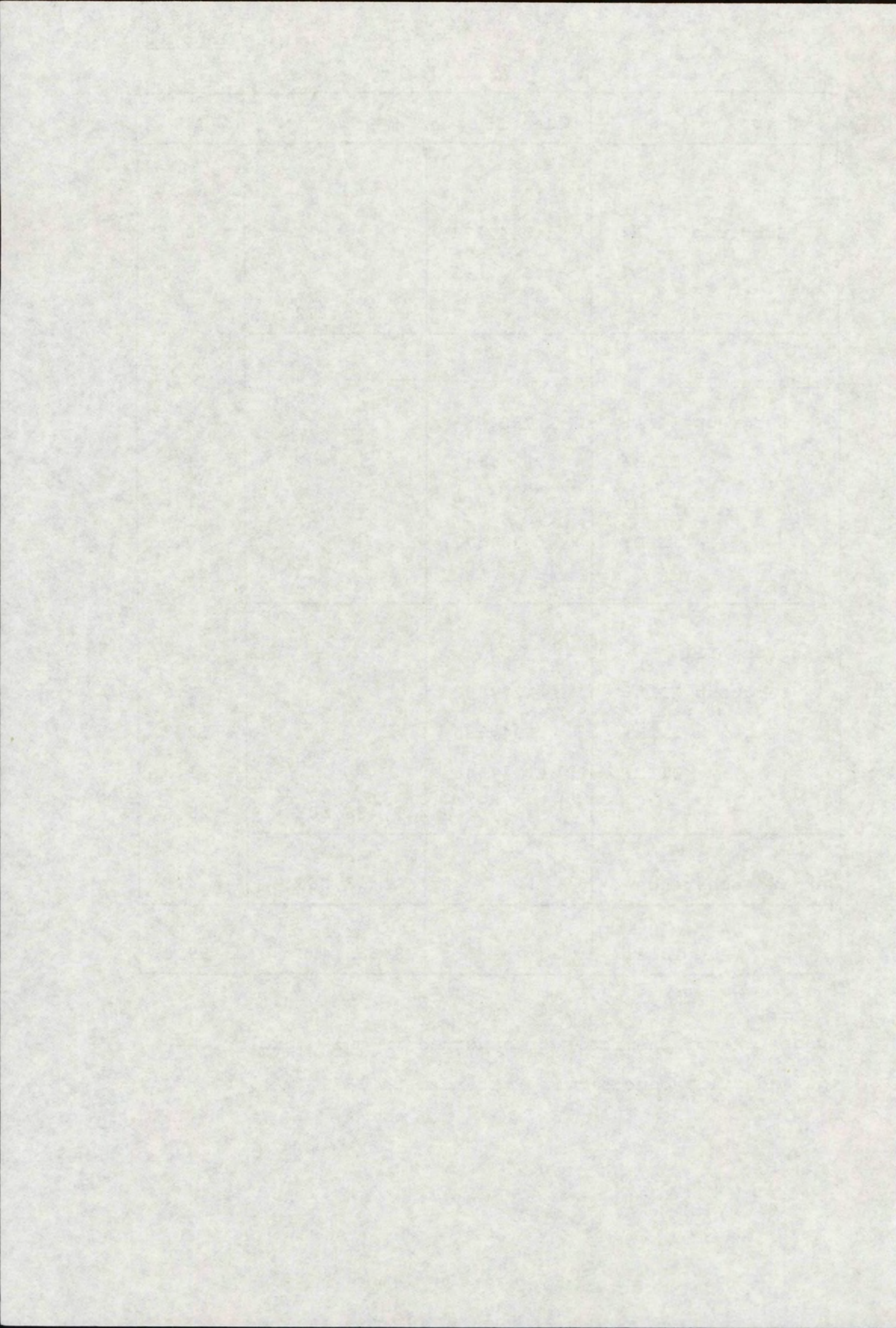


TABLE 1.

Group	Quantity in m ³		%
Maingroup I:			
Subgroup I A:	44,321		0,4
" I B:	650,893		6,6
		695,214	7
Maingroup II:			
Subgroup II A:	3,758,749		38,8
" II B:	1,127,117		11,7
" II C:	1,108,068		11,4
" II D:	90,671		0,9
		6,084,605	62,8
Maingroup III:			
Subgroup IIIA:	1,127,632		11,6
" IIIB:	1,234,585		12,7
" IIIC:	124,588		1,3
		2,486,805	25,6
Unknown substances		418,866	4,3
Total		9,685,490	99,8

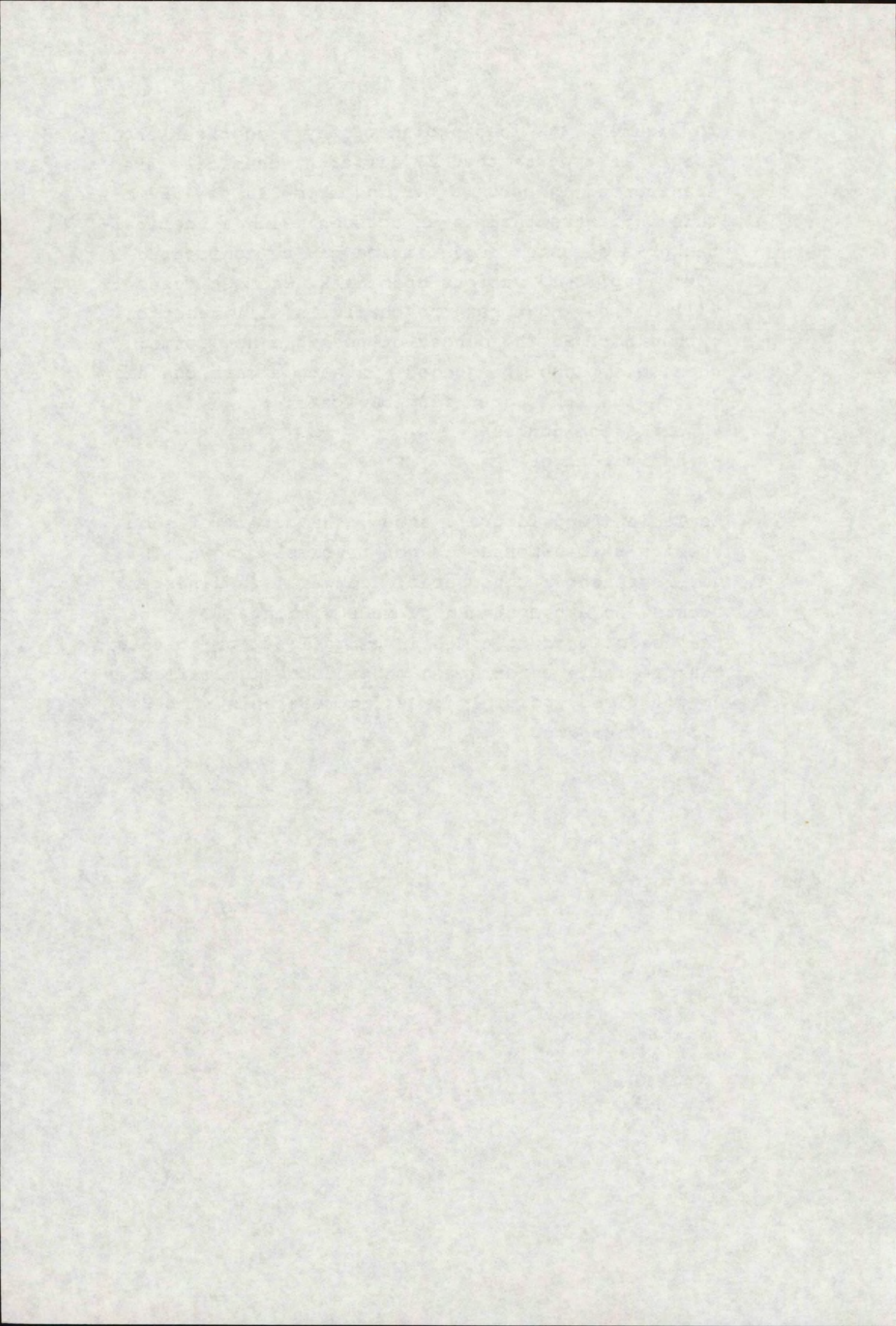
Quantities of chemicals transported in bulk (excl. crude oil and oil products) via Rotterdam in 1979 (m³).



In figure 3 the loading plan of any product tanker is shown. It appears that 27 different chemicals are transported in parcels varying from 240 to 1360 m³. This indicates that in an accident with a chemical-tanker a disaster organization can be confronted with a spill of various chemicals. In most cases it will not be known how the chemicals will react on each other. So the danger of possible new formed chemicals cannot be judged. In such a case one has to consider the worst possible case:

- explosion danger
- health danger.

As Table 1 and figure 3 show , the nature of some chemicals transported is not precisely known. This may represent a considerable danger if a disaster occurs. An attempt must be made within IMCO to ban the use of product names in cargo lists or to ensure that reliable information on products is available at all times, possibly by using reference numbers, e.g. UN numbers.



3. Behaviour of gas and vapour clouds: Main Group I

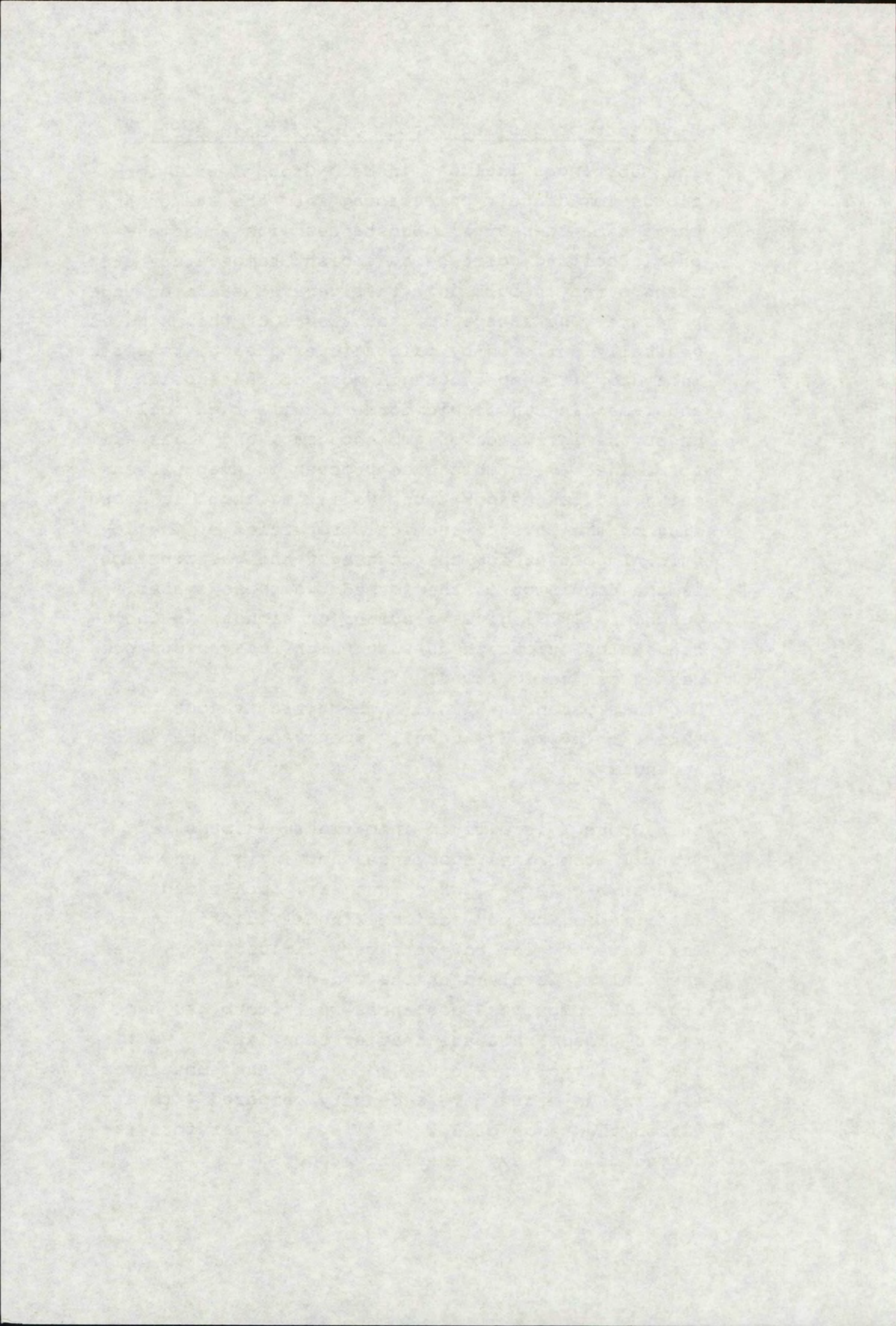
The substances included in Main Group I will form clouds immediately on escaping into the sea or a short time thereafter. Substances with an atmospheric boiling point below ambient temperature are transported in bulk in a refrigerated state or under pressure. The escape of a substance of this kind is generally followed by adiabatic expansion, resulting in a drop in temperature in most of the substance and remaining in liquid form. It will then boil under the influence of ambient heat, and a gas will form. The way in which the process of evaporation known as flashevaporation, will come about is depending on the physico-chemical properties of the liquid. Important for the course of the gasification is the condition of the formed two phase system. Opschoor (1979) gives a number of situations including calculation methods with which the various processes can be followed.

Liquid substances with a high partial vapour pressure (> 150 mm Hg) usually evaporate quickly (see Appendix I).

Main Group I is divided into two sub-groups.

Group IA comprises substances forming gas and vapour clouds which are lighter than air. Such clouds will rise, making proper action extremely difficult. This category is, however, very limited. Only one chemical is involved at the moment: ethylene.

Group IB comprises substances which form gas and vapour clouds that are heavier than air. If we take the density of air to be 1, most of the substances in this sub-group have a density compared with air within the range of 3 to 7. They are therefore referred to as heavy gases and vapours.



As disaster organizations cannot as a rule be on the spot until some hours after the accident, they will usually be dealing with substances in the gas or vapour phase where Main Group I is concerned. Action must therefore be taken accordingly. It is also important to establish how gas and vapour clouds have spread. In this, computational models have an important role to play.

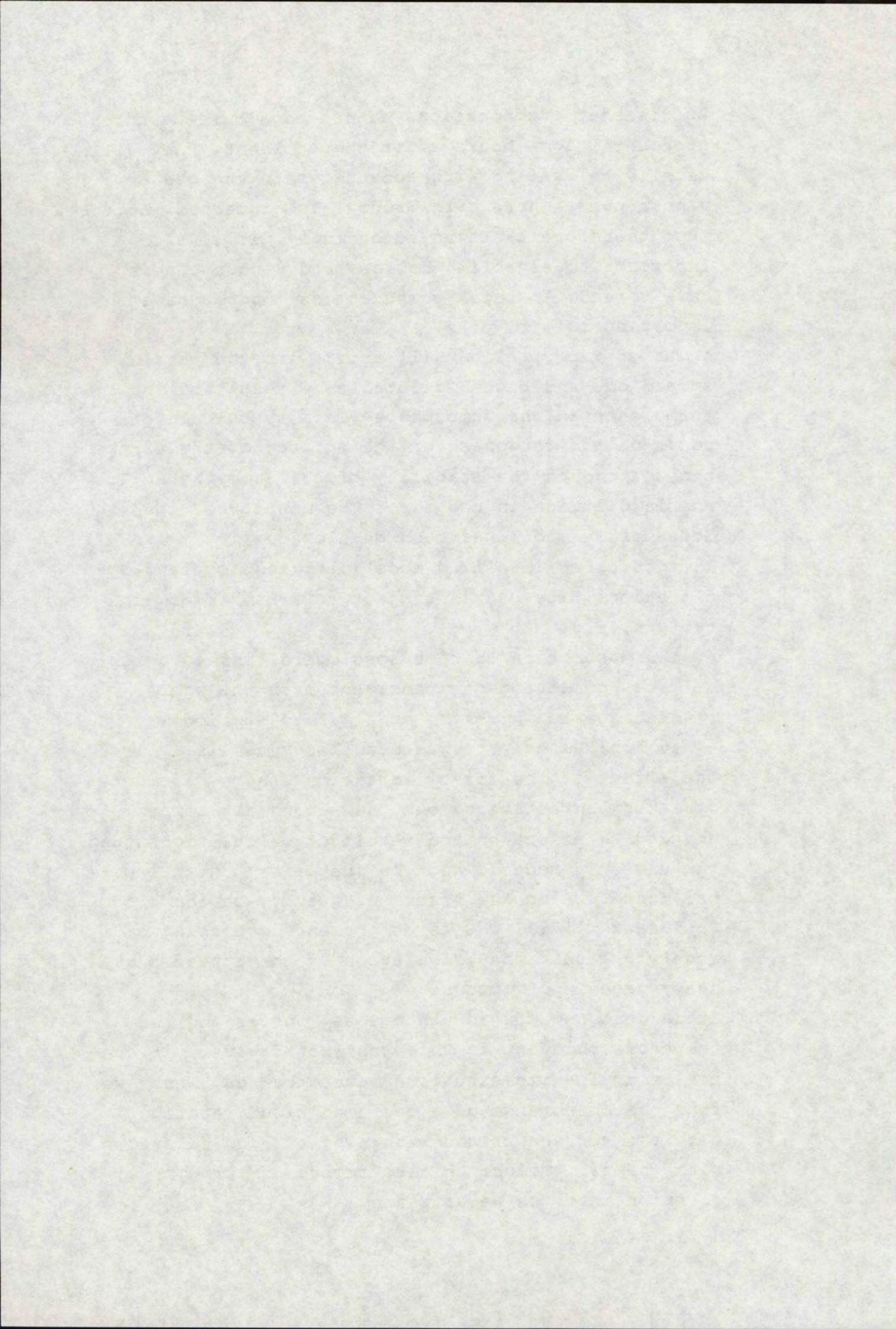
A gas or vapour cloud will drift with the wind, spread out and become diluted as a result of the turbulence in the atmosphere. This turbulence depends on the roughness of the surface of the earth and sea and on the stability of the atmosphere. To enable dilution in the air to be monitored, the Gauss plume model has been developed.

As this is an idealized model designed for land applications, its use is subject to a number of limitations, e.g.

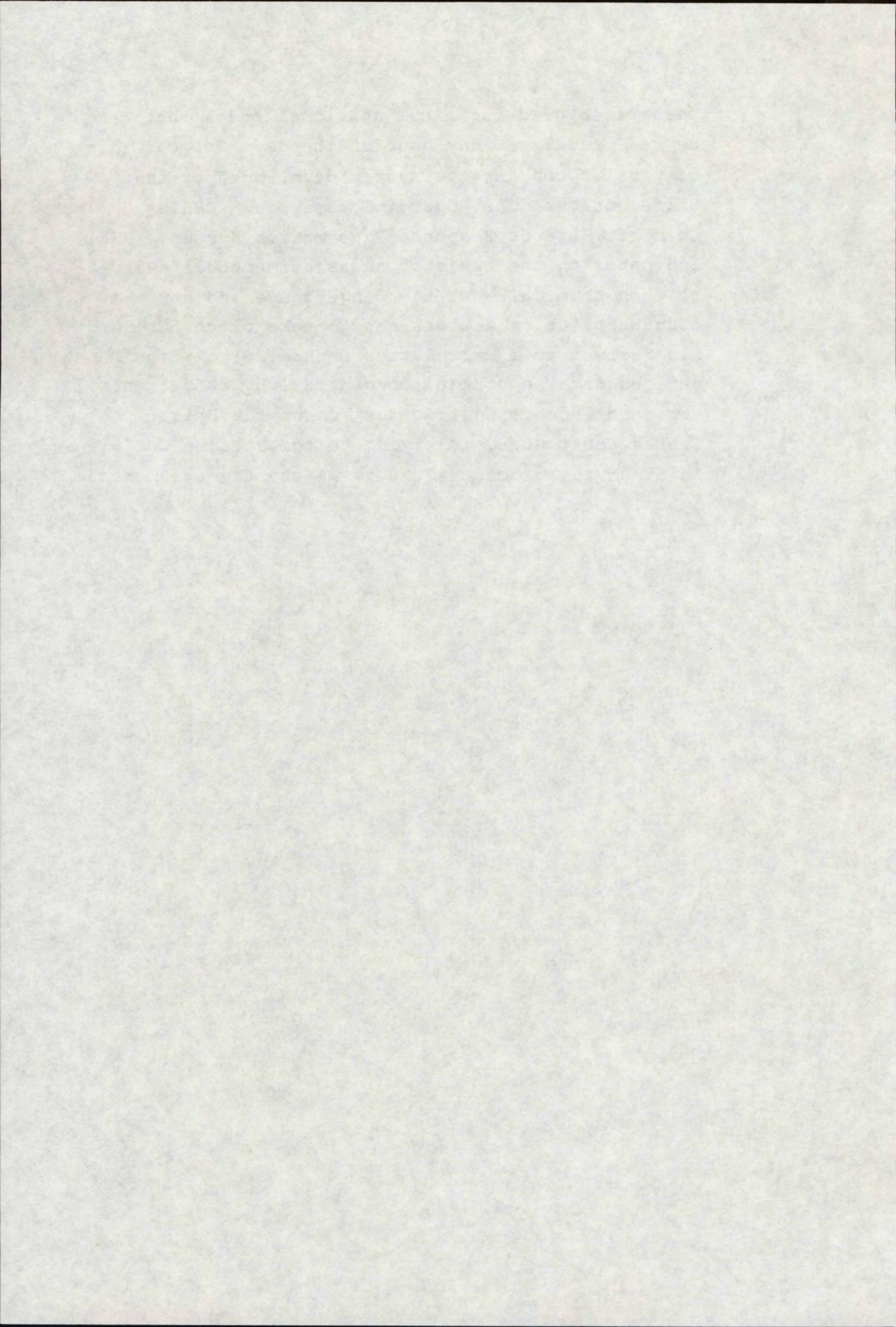
- the assumption that meteorological and topographical conditions are constant over the whole distance to which the model is to be applied
- it applies only to gases as heavy as air.

The effect of the first limitation can be discounted by making an estimate, but the second has so pronounced an effect on the result of calculations that the use of a model cannot be justified, the principal factor being the effect of gravity on the cloud (Buytenen, 1979). TNO is at present developing a model to permit the calculation of the spread of heavy gases and vapours.

It is designed for instantaneous sources and is therefore relevant in this context. However, it cannot be applied to situations over the sea, where we find the phenomenon of a drifting cloud reacting with the surface of the water while being diluted with the air. Reduction also occurs through absorption into the water phase.



There is a need for a computational model that can be used easily at any hour of the day. One can think of partial copying the system developed by the United States Coast Guard. This system (CHRIS= Chemical Hazards Response Information System (1978)) indicates on the basis of an assessment code awarded to each chemical what the dangers are and how counterpollution actions has to take place. The code also refers to a calculation method, with which various data as spread, concentration, danger zones, etc. can be obtained. At the moment the United States Coast Guard is trying to computerise CHRIS. An disadvantage of the system is the use of American units.



4. Detection of gas and vapour clouds

As most gases and vapours are colourless, it is impossible to see where a cloud is located.

In view of the need to measure concentrations, detection apparatus must therefore be used. When trying to detect a gas or vapour cloud, a ship must always approach it from upwind to avoid undesirable exposure.

4.1 Gas detection with the help of direct measurements

There are already a lot of detection- and measuring systems which are capable of detecting dangerous gasses. The lot of those devices operates on land as well as on shipboard. They vary from simple portable sets to permanent installed continuous monitoring systems. An example of a simple set is the Dräger tube. This is a glass tube filled with a substance which reacts to a specific substance being sought by changing its colour.

Air is inducted with the aid of small bellows, and the degree of discoloration then corresponds to the concentration of the pollutant in the air (see Fig. 4). Each tube can be used only once. As there are many different types of gases and as many measurements are needed to ascertain what danger is involved, a considerable assortment of Dräger tubes has to be available.

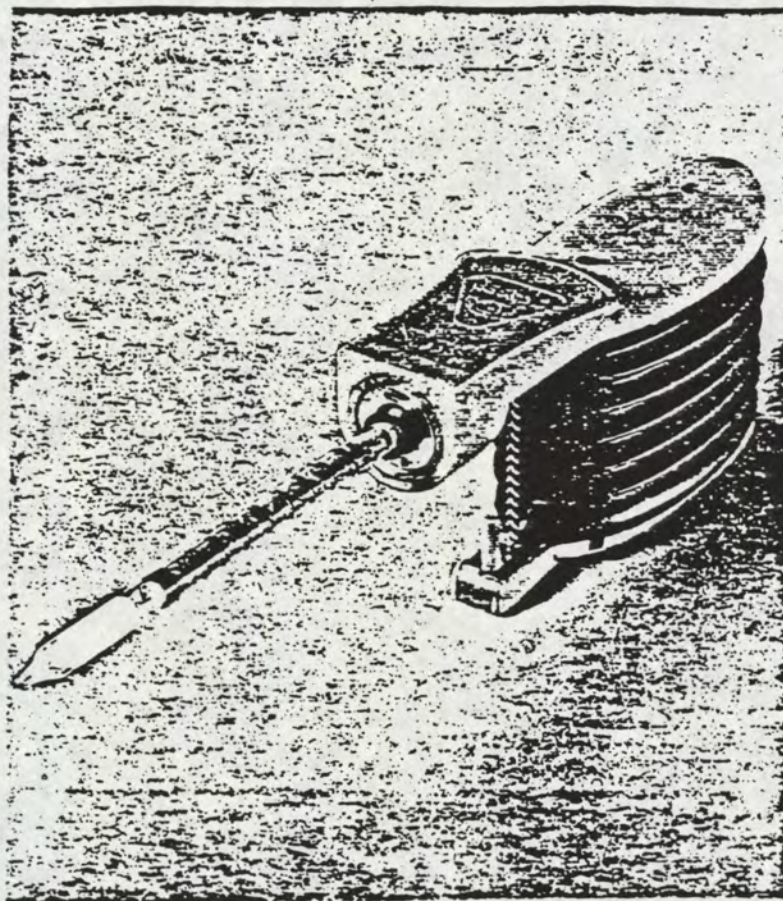
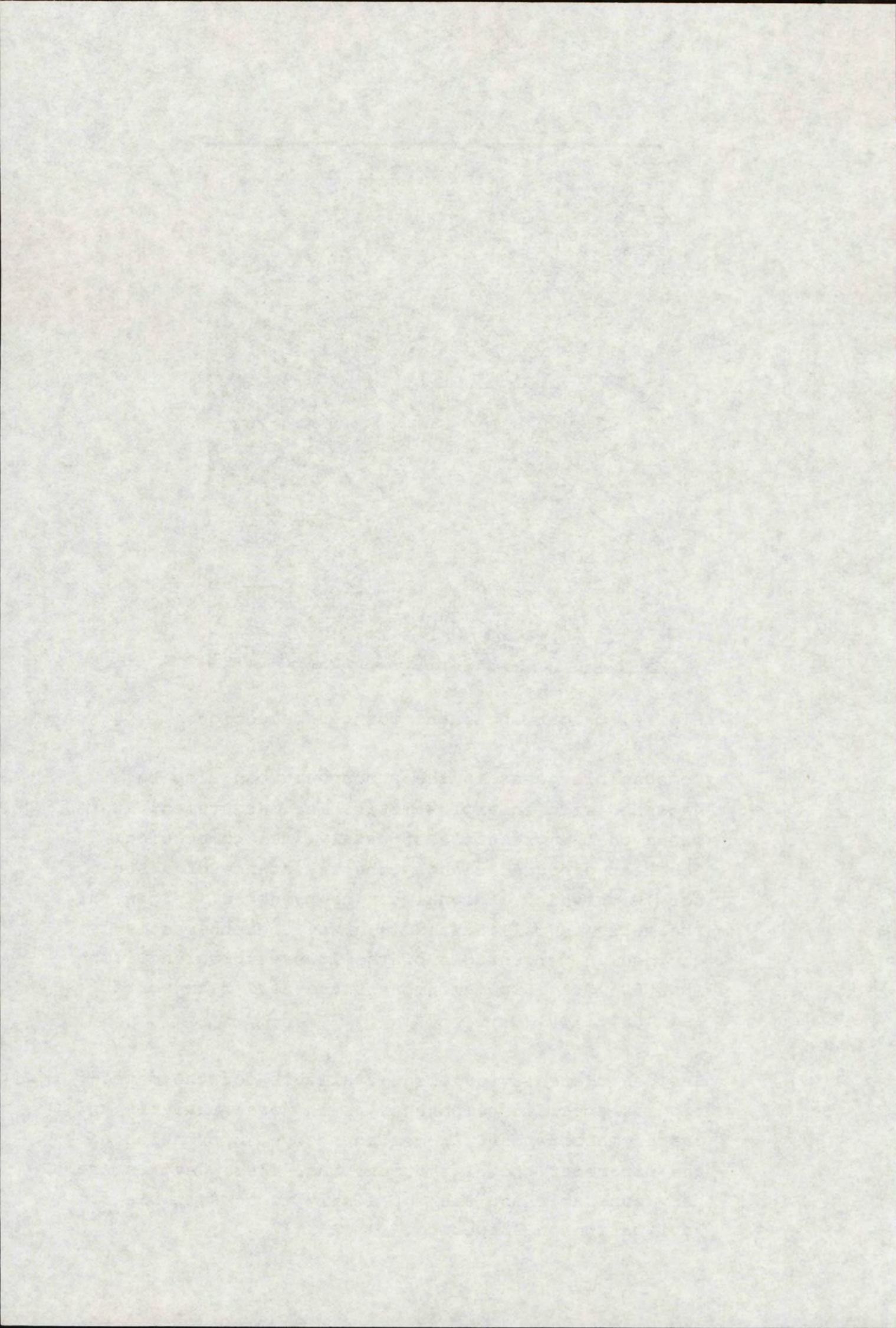


Fig. 4. Drager apparatus for gas detection.

Combustible gases in the atmosphere can also be detected with an explosimeter. The measurement is based on the principle of catalytical combustion. The heat produced changes the resistance of a sensor, with which a signal can be produced. In general the meter is calibrated in a way that the scale is divided in percentages of the lower explosion limit (see 5.1.1.). Explosionmeters are used both portable and installed.

Besides there is equipment available for the detection of specific components as infrared analyses and gaschromatographs. C_xH_y -monitors give information on the parameter: total hydrocarbons. These devices are very vulnerable and are not likely to be suitable for application on shipboard.

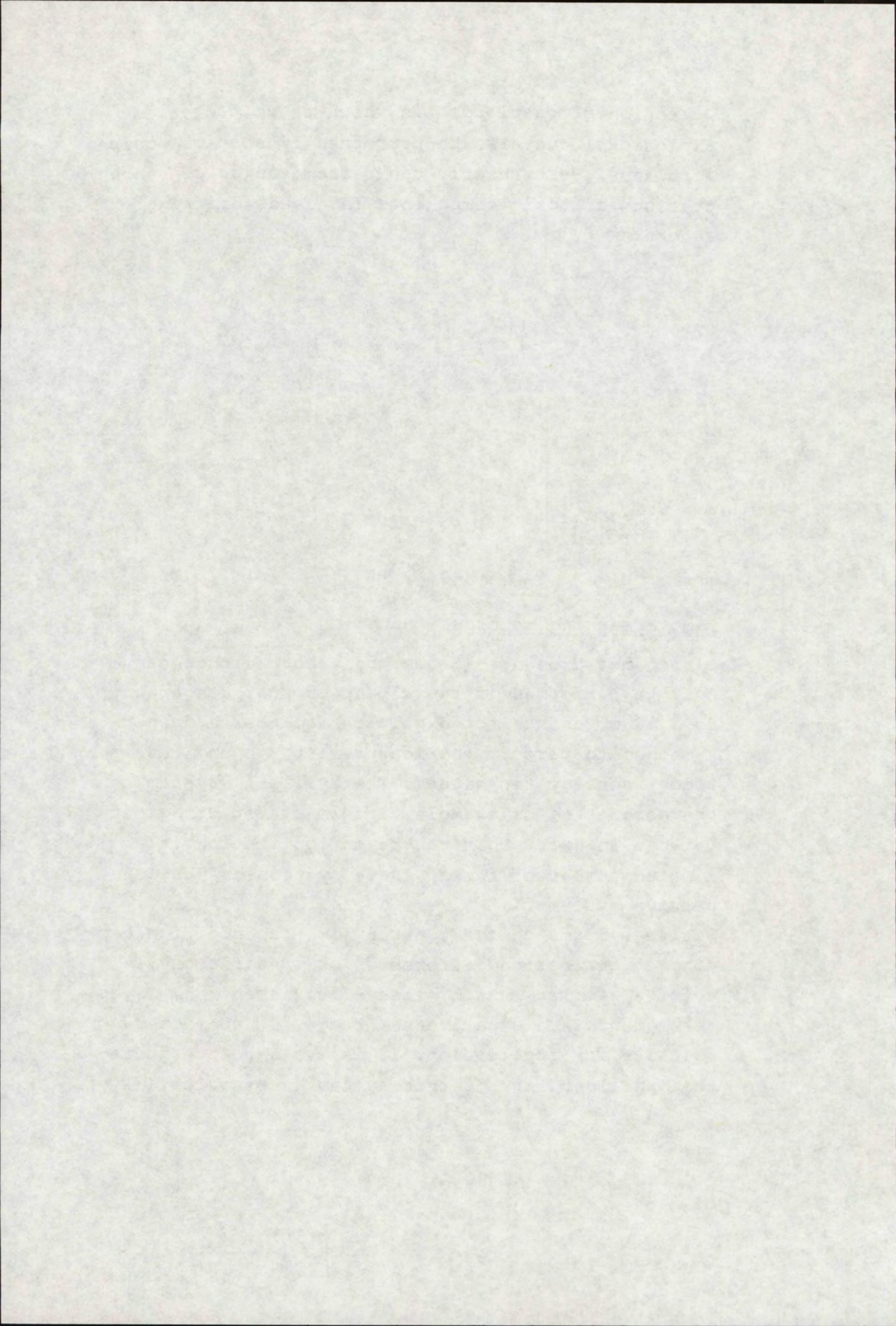


Detection of gasclouds (in which is no danger for explosions) can also be performed by special equipped airplanes. Particularly the determination of concentrations of toxic components in clouds drifting ashore.

4.2 Remote_sensing_methods

Direct measurements in gas and vapour clouds can only be performed if the clouds are not dangerous. So a minor chance for explosion and health danger. A method to perform the measurements in any case are remote sensity techniques. The available system at the moment is for example capable of detecting difference in heat. This can be an application in a limited number of cases. These systems are called passive systems.

Active systems on the contrary are capable of detecting concentration differences of specific chemicals. A similar system, laser-fluorescentron, is at the moment in a experimental stage. It seem to be suitable for application. It is avaisable to judge the applilcability of this system in practice.



5. Dangers of gas and vapour clouds, and appropriate action

The dangers of gas and vapour clouds are limited in the marine environment. Man, on the other hand, is exposed to danger in his efforts to dealing with such clouds. These dangers include fire and explosion and the risk of health being affected by the toxic properties of the substances concerned.

5.1 The risk of fire and explosion

5.1.1 Explosion limites, etc.

Where a gaseous or evaporating substance escapes, an explosive or combustible mixture may form.

An explosive mixture occurs if the gas concentration in the cloud (local) is between the upper and lower explosion limits (Fig. 5).

If the lowest concentration in the cloud is above the upper explosion limit, only combustion can occur. Where combustion occurs, the concentration may fall below the upper explosion limit as a result of dilution and an explosion may then follow.

There is no danger of a fire or explosion if the maximum concentration in the cloud is below the lower explosion limit.

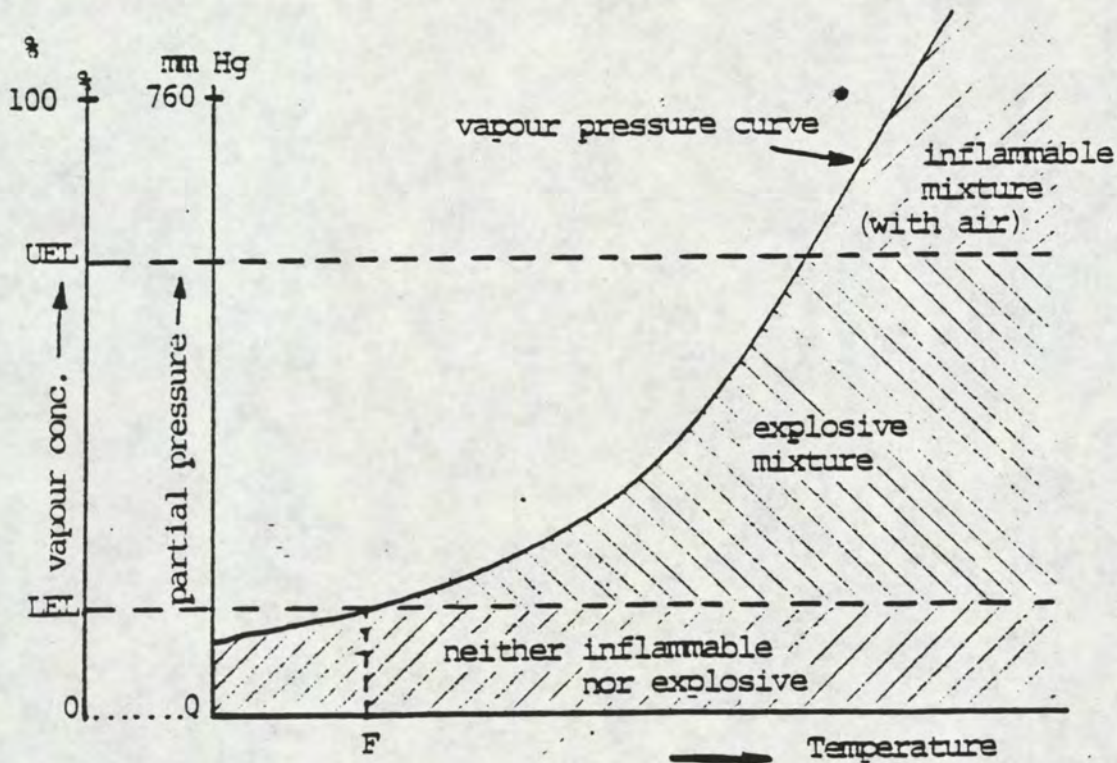


Figure 5. The connection between partial pressure, temperature, vapour concentration, upper explosion limit (UEL), lower explosion limit (LEL) and flashpoint (F) in relation to the danger zones.

As a measure of the danger of gas and vapour clouds exploding we thus have the lower explosion limit (LEL) and the upper explosion limit (UEL), expressed as volume percentages.

As a measure of the danger of the combustion of liquids the flash point is used. The flash point (measured in °C) of a combustible liquid is the lowest temperature at which the gases it gives off form an ignitable mixture with air.

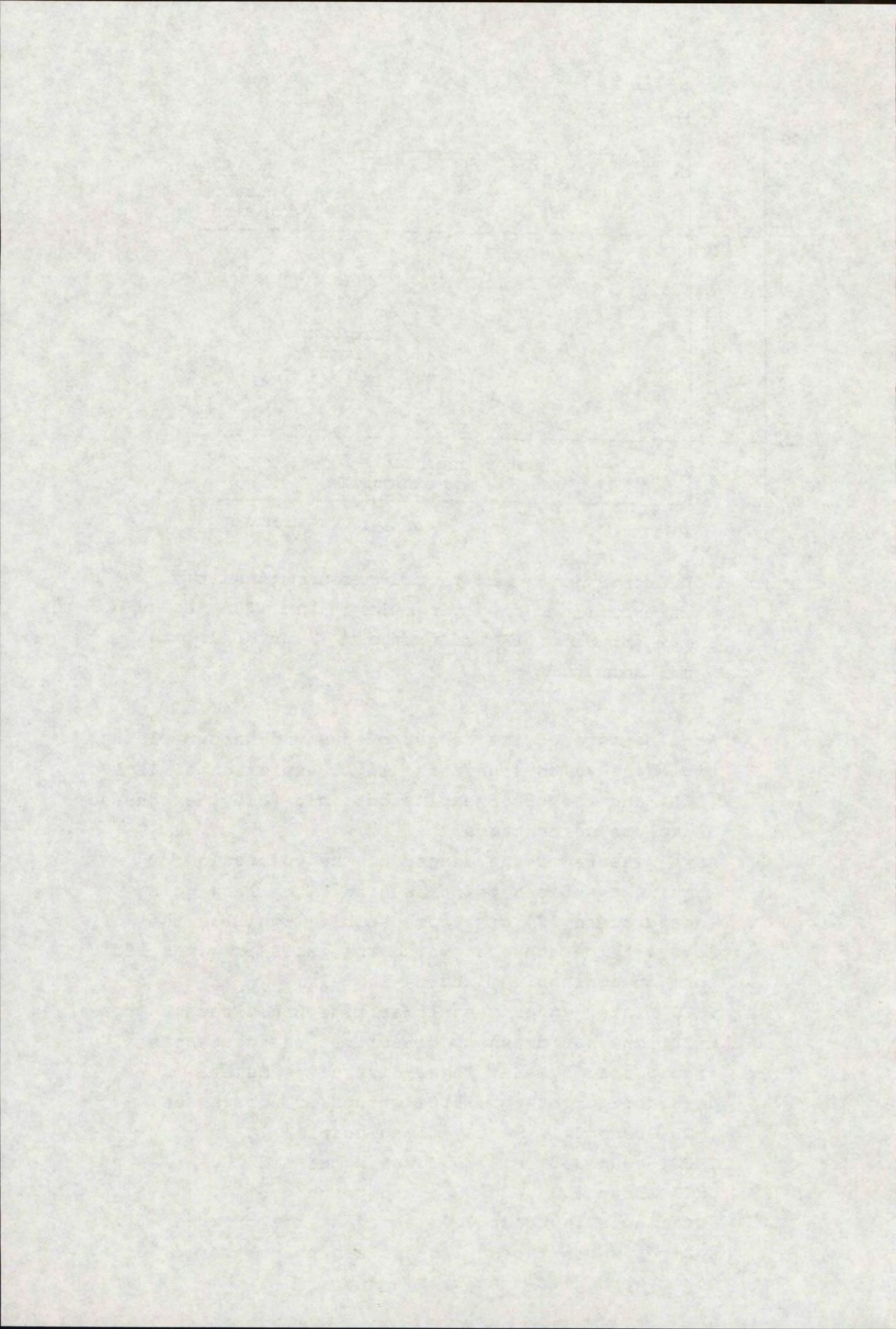
IMCO (Inter-governmental Maritime Consultative Organization) has drawn up directives on substances transported by sea. These directives make a distinction between three groups of substances:

IMCO Group 3.1 flash point $\leq 18^{\circ}\text{C}$

IMCO Group 3.2 $-18^{\circ}\text{C} < \text{flash point} \leq 23^{\circ}\text{C}$

IMCO Group 3.3 $23^{\circ}\text{C} < \text{flash point} \leq 61^{\circ}\text{C}$.

Substances in Group 3.1 represent the greatest fire hazard, while those with a flash point over 61°C are not regarded as dangerous.



5.1.2 The occurrence of fire and explosions

A fire or explosion can occur only if three requirements are simultaneously satisfied. These three requirements form the "combustion triangle" (Fig. 6).

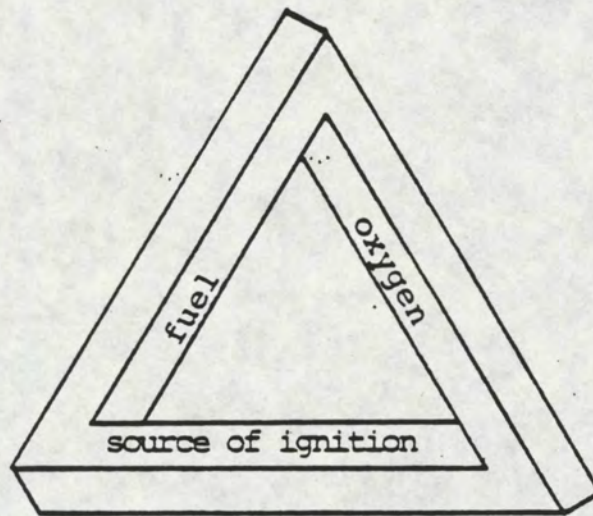


Fig. 6: combustion triangle.

Possible sources of ignition are:

- open fire
- impact
- friction
- local heating
- electrostatic or mechanical sparks
- (radio-active) radiation
- noise.

If the energy content of the source is greater than the ignition energy of the gas and vapour mixture, a fire or explosion may occur.

Where an accident has occurred, shipping and aircraft must always be warned because ships and aircraft also represent potential sources of ignition.

Where a quantity of gas compressed to liquid form escapes, ignition is very likely. A study of escaping LNG puts the probability at 65% (Snellink, 1978). A possible source of ignition in this case would be a discharge of static electricity.

5.1.3 Extinguishing fires

A fire is extinguished by eliminating one of the factors in the combustion triangle:

- removing the fuel
- removing the oxygen
- removing the source of ignition.

In most cases, a combination of these basic methods is used. The following briefly describes how these basic methods can be applied.

5.1.3.1 Removing the fuel

It is usually difficult to remove the fuel during a fire.

It may be possible to stop the inflow of fuel, for example by shutting off the source from which the liquid and gas are escaping. Another possibility is to allow the fire to burn out under controlled conditions.

5.1.3.2 Removing the oxygen

Reducing or removing the oxygen present can be accomplished in two ways:

- (a) Preventing the flow of fresh air to the seat of the fire. The combustion reaction then uses up the oxygen present and the fire goes out. This method is applied by covering a burning surface with foam. The combustible substance is separated from the air, which puts out the fire.

- (b) The oxygen is displaced through the introduction of an inert gas. In theory, any gas or vapour that will not take part in the combustion reaction can be used for this inerting process.

Examples of such substances used to extinguish fires on land are nitrogen, carbon dioxide and steam.

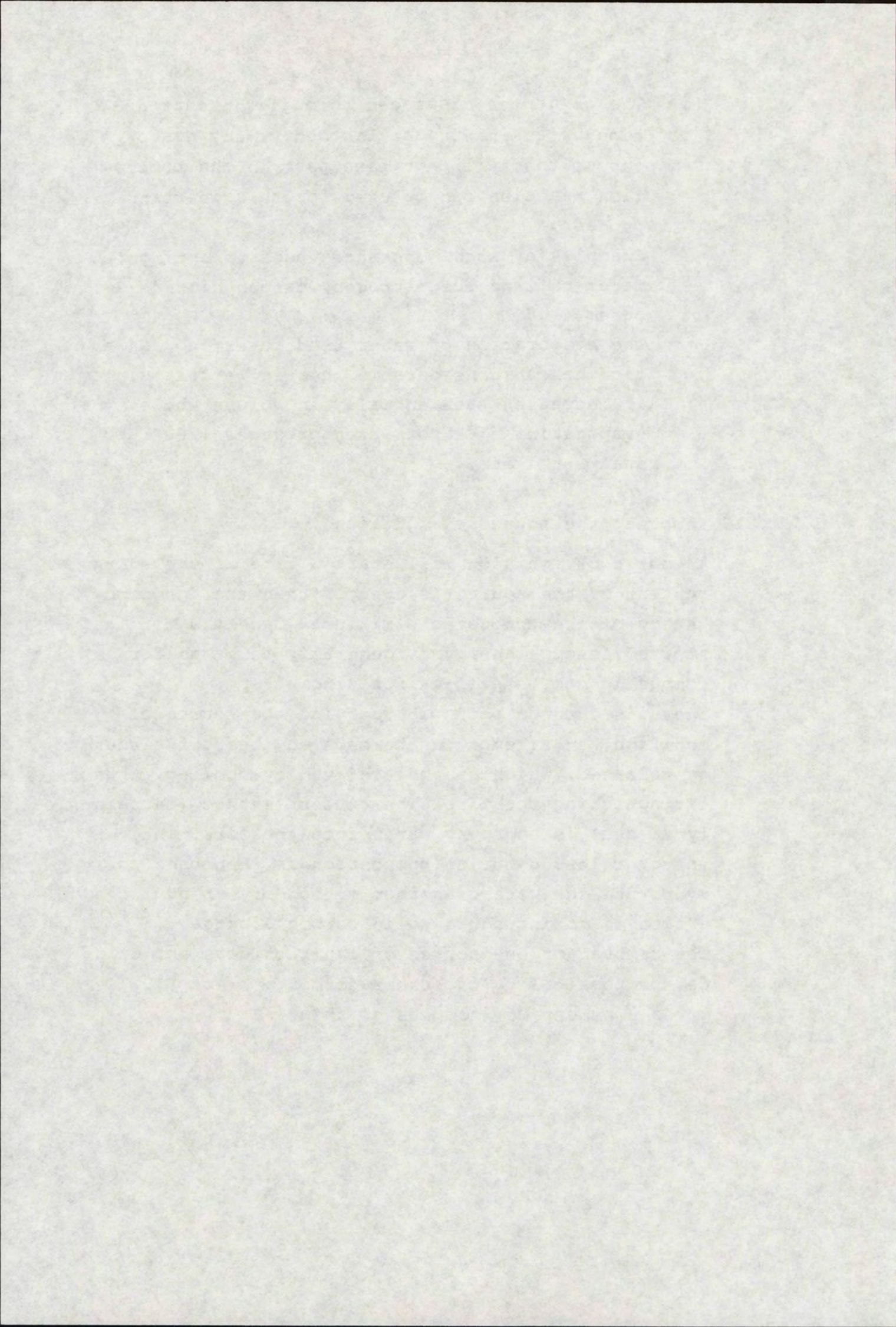
The evaporation of water used to extinguish a fire has an considerable inerting effect since it increases substantially in volume while evaporating (1 kg of water produces 1700 l of steam at 1 atm.).

5.1.3.3 Removing the source of ignition

A source of ignition will start a fire if the energy content of the source is greater than the ignition energy of the combustible mixture. Once the fire has started, enough energy is generally released for combustion to be self-maintaining.

There is then no point in removing the source of ignition. An attempt can be made to absorb the energy released, which can be achieved by cooling, thus extinguishing the fire. The easiest method (certainly at sea) is to spray water into the fire. The energy released during combustion is then used to evaporate the water. Another method of extinguishing a fire is to introduce solid carbon dioxide.

The removal of one source of ignition does not exclude the possibility of others forming. Kletz (1977) gives a number of examples of this.



5.2 Health hazards caused by toxic properties

Among the chemicals transported in bulk by sea there are a number of substances which form a poisonous gas cloud when they escape. In general, intoxication can occur along three different routes:

- the digestive organs
- the skin
- inhalation.

In the case of toxic clouds, primary intoxication will occur through the inhalation of the toxin.

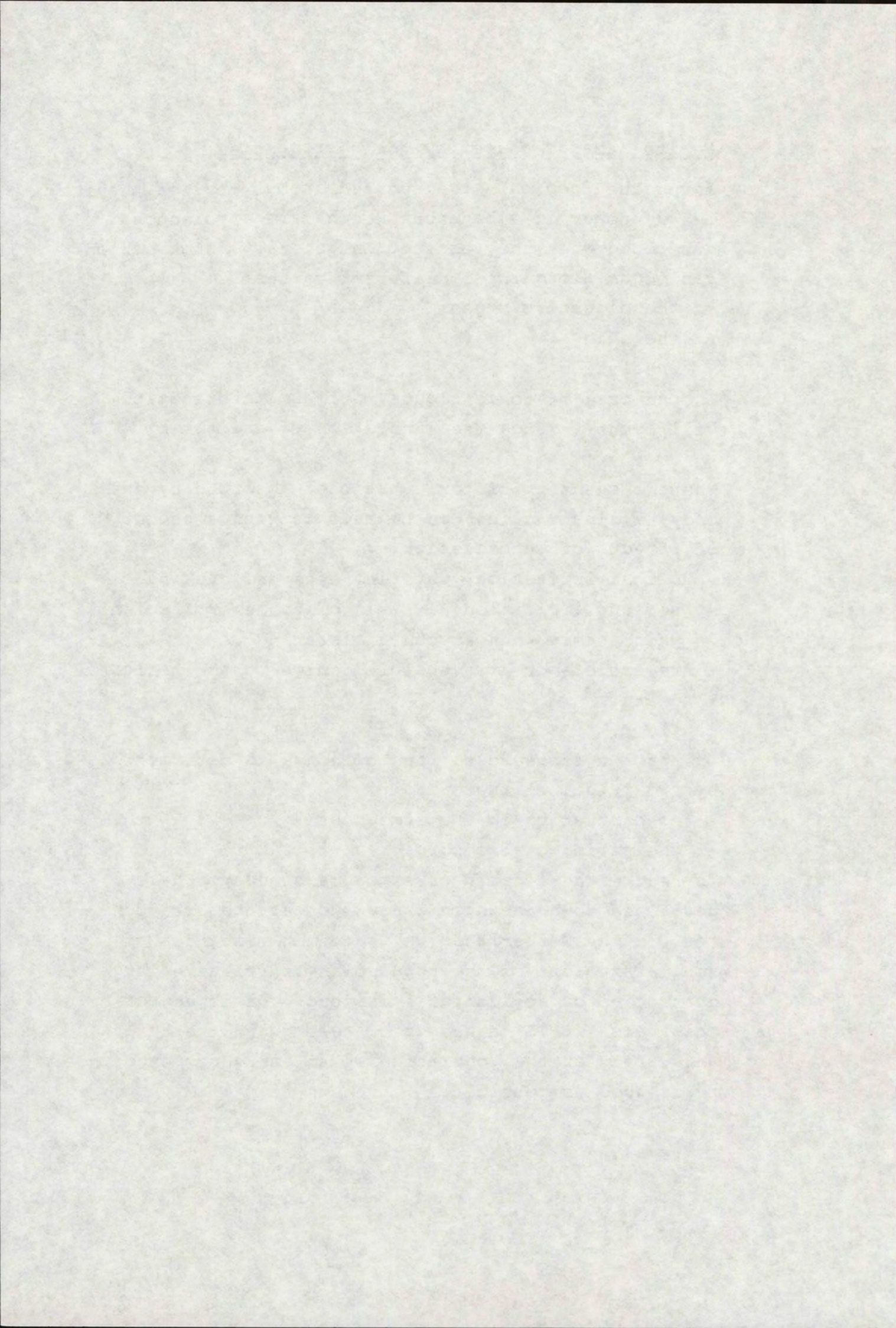
Where a quantity of toxin has been absorbed by the body, a distinction can be made between a number of effects of intoxication:

- slight irritation, watering eyes and choking
- serious irritation, i.e. intolerable irritation which stops when exposure ceases
- reversible or irreversible damage to the health
- death.

The effect exposure to the toxin has is determined by two principal factors:

- concentration in the atmosphere
- the period of exposure.

To reduce the effects of exposure standards have been laid down in which these two factors are counted. In the Netherlands we use limit values for a single exposure of the population to relative large quantities of accidental emissions. the object of this value, EPEL-value, is to safe guard the health and safety of the population at an emergency exposure as good as possible.



In table mentioned below a number of proposed EPEL-values are given:

	1/2 hour	1 hour	2 hours
acetonitril	160	80	40
arylonitril	40	20	20
allylchloride	4	2	1
ammonia	50	25	25
chloor	1,5	1	1
ethyleenoxide	200	100	50
fosgeen	0,13	0,06	0,03
methylbromide	30	15	15
zwavelwaterstof	1-2	1-2	1-2

Table 2 Proposed EPEL-values in the Netherlands
(in ppm)

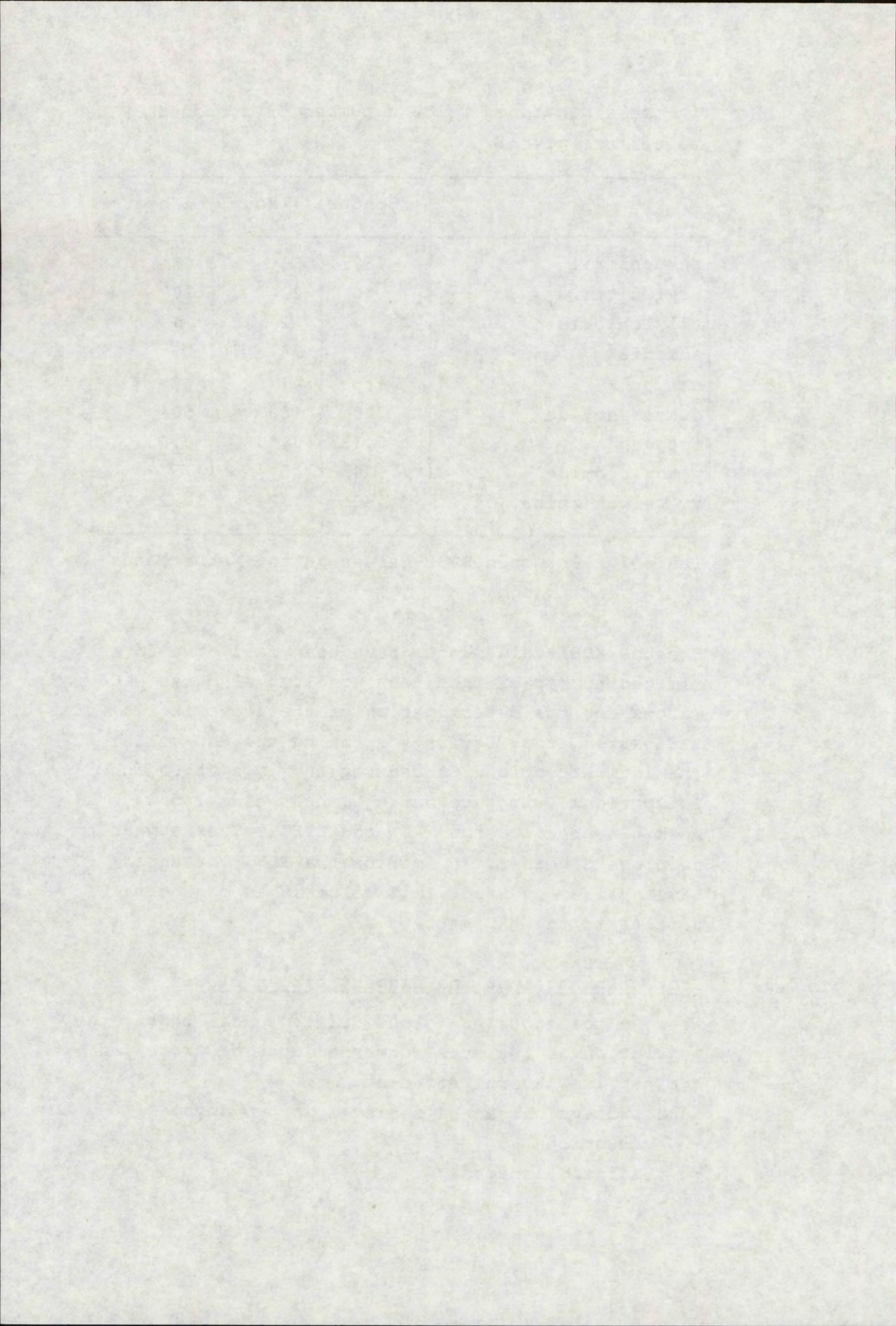
Because EPEL-values only have been laid down for a limited number of chemicals, one can also use MAC-values for the determination of the accessibility of a disaster area. Strictly speaking the MAC-value (Maximum Acceptible Concentration) is a value for occupational exposure during 8 hour a day, 5 days a week. In practice the MAC- and EPEL-values appear to be close together. In America the TLV (Threshold Limit Value) is used. This value is in many cases similar to the MAC-value.

5.3 Protection against the dangers of gas clouds

Where a poisonous gas cloud drifts to the coast, the population of the area concerned must be protected against its harmful effects.

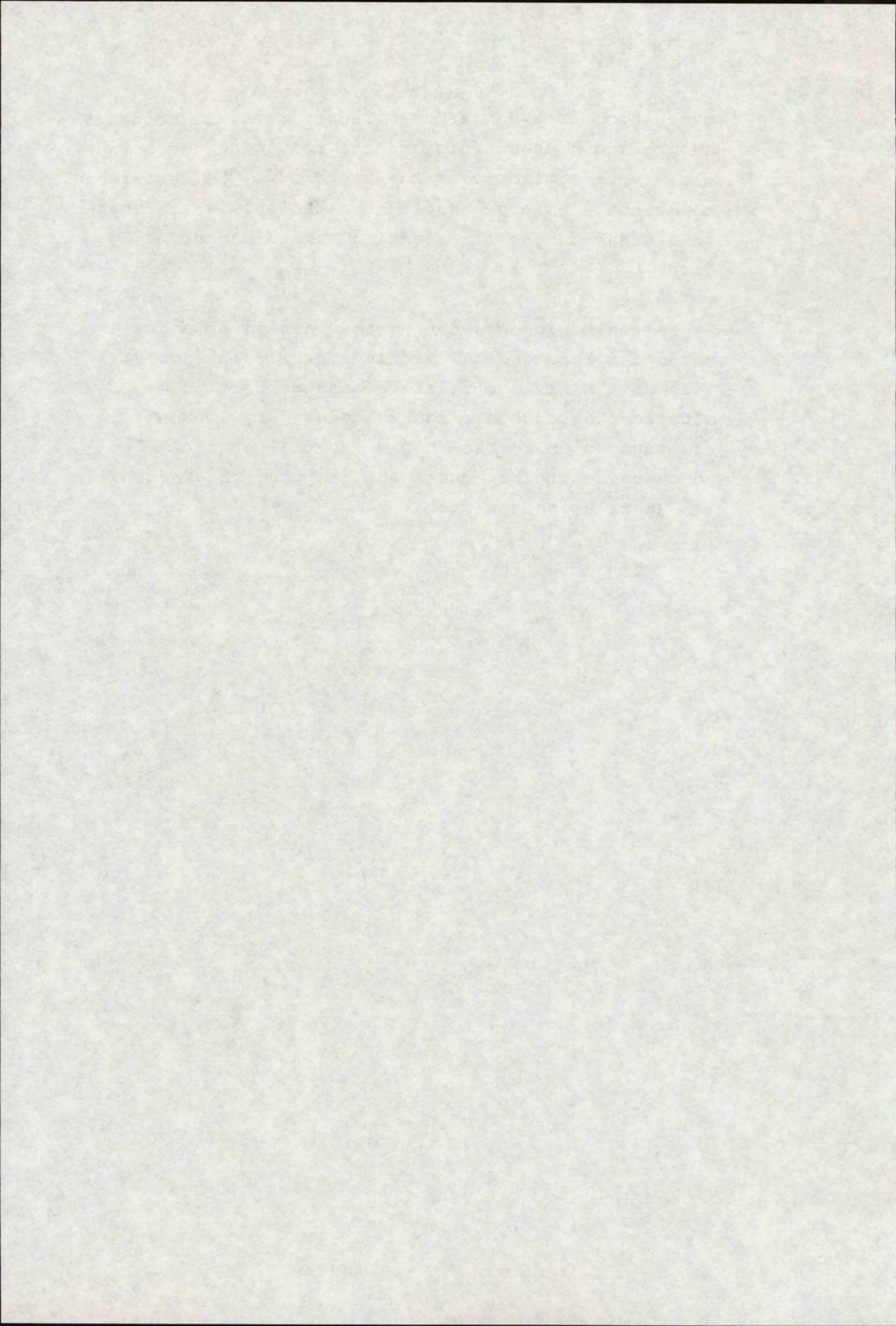
Such protection can be achieved in two days:

- evacuation
- remaining indoors.



Evacuation is a dangerous measure, several incidents having shown that panic and the resulting chaos may claim more victims than the gas cloud. The decision to evacuate an area should be taken only where there is a grave danger of poisoning and/or danger of fire.

By remaining indoors during the passage of a gas-cloud and reducing the exchange of air in and outside to a minimum a relative safe protection can be offered. The exchange can be reduced by locking all the gaps, closing the chinks (special at the weatherside of the house) and stopping the mechanical ventilation equipment.



6. Behaviour of spills: Main Group II

Substances in Main Group II will float on the water. In addition, the substances in Sub-groups IIA and IIC evaporate to such an extent that the possibility of a vapour cloud must be considered. The substances in Sub-groups IIC and IID will form clouds of the products of their reaction with water. After escaping, the substance will spread out on the water (spreading), where it will then be affected by external factors such as wind, waves and tidal currents (displacement). While these secondary spread phenomena continue, various natural degradation processes occur.

6.1 Spreading

Spreading is caused by the combined effect of the potential energy the escaping liquid possesses on coming into contact with the water, and the surface tension of the liquid.

According to Fay (1969), spreading can be subdivided into a number of phases. As the final result he presents an approximation formula for calculating the surface of a circular spill on the basis of the volume of escaping substance:

$$A = 10^5 V^{\frac{1}{2}}$$

Fay developed this formula to calculate the spread of oil on sea water his assumptions being that:

- the properties of the liquid do not change while it is spreading;
- the sea is calm while the substance is spreading;
- the oil is distributed homogeneously over a circular area.

As the properties of the substances in Group II undergo little or no change while they are spreading, it is not unacceptable for these formulae to be applied to these substances.

6.2 Displacement

Of the many physical processes causing the displacement of a spill, the wind and tidal currents are the most important.

The effect of waves on the displacement of the floating substance is very limited and can therefore be ignored in this context.

A linear connection clearly exists between wind speed, measured 10 metres above the surface of the water, and the speed of the movement of the spill as calculated by the formula (Teeson, 1970).

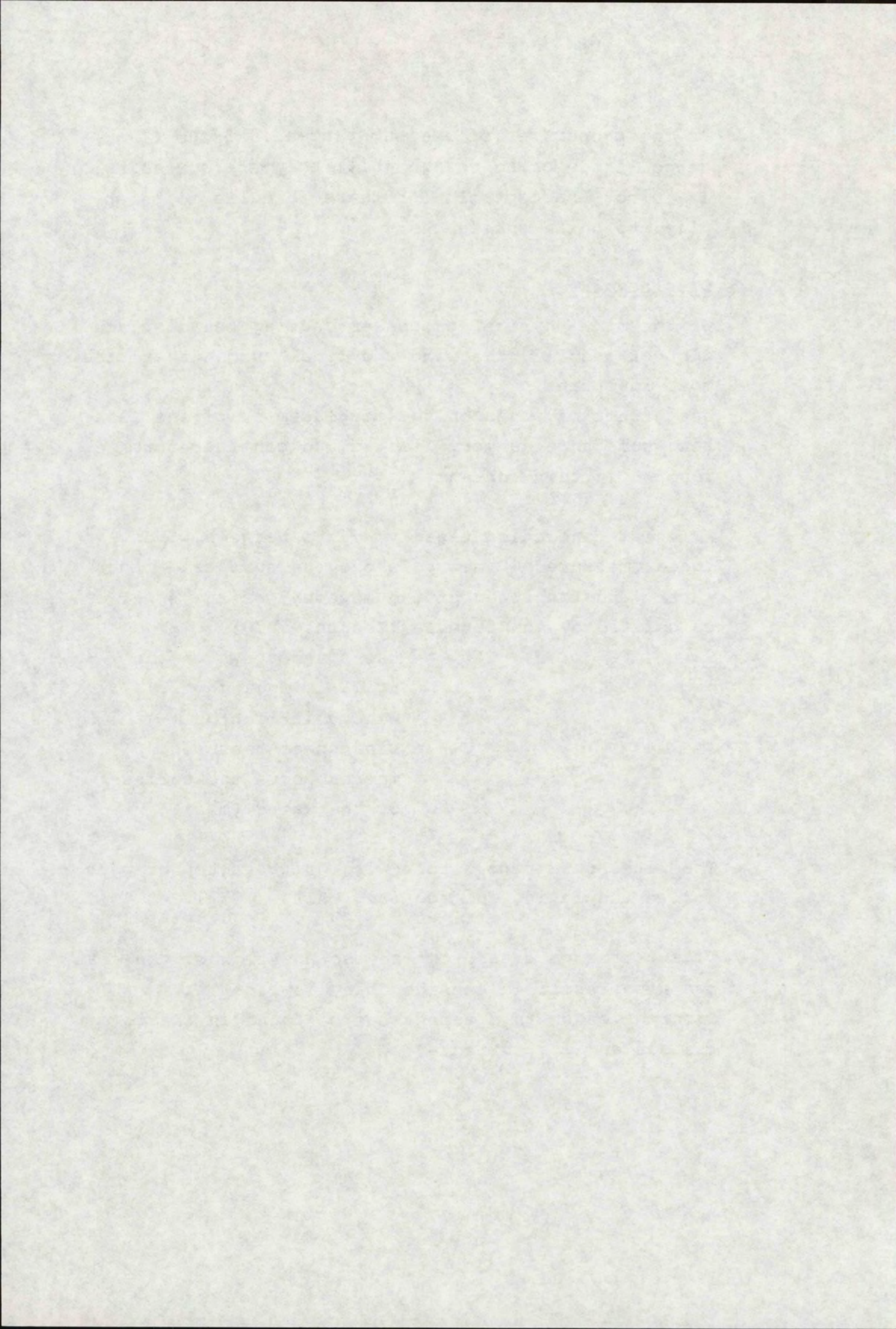
$$u_0 = f \times U_{10}$$

u_0 = the speed at which the spill is moving (m/s)
 f = wind drift factor (-)
 U_{10} = wind speed measured 10 metres above the surface of the water (m/s)

The literature refers to a wind drift factor of $\pm 3\%$ for an undulating surface (e.g. Alle, 1977).

Tidal currents caused by the ebb and flow of the sea can also result in considerable displacement.

Information on this aspect can be found in charts of the sea and its currents.



Ultimate displacement is the sum of the current and wind vectors.

$$u_v = u_{\text{current}} + 0.03 u_{10} \text{ wind}$$

or, translated into a vector diagram:

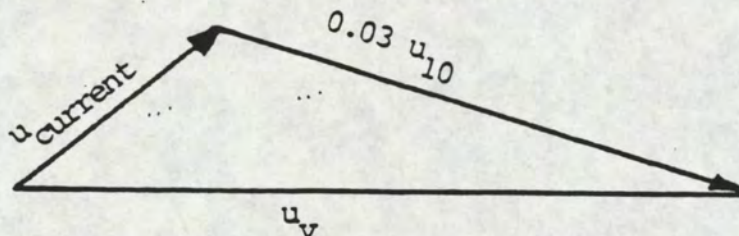


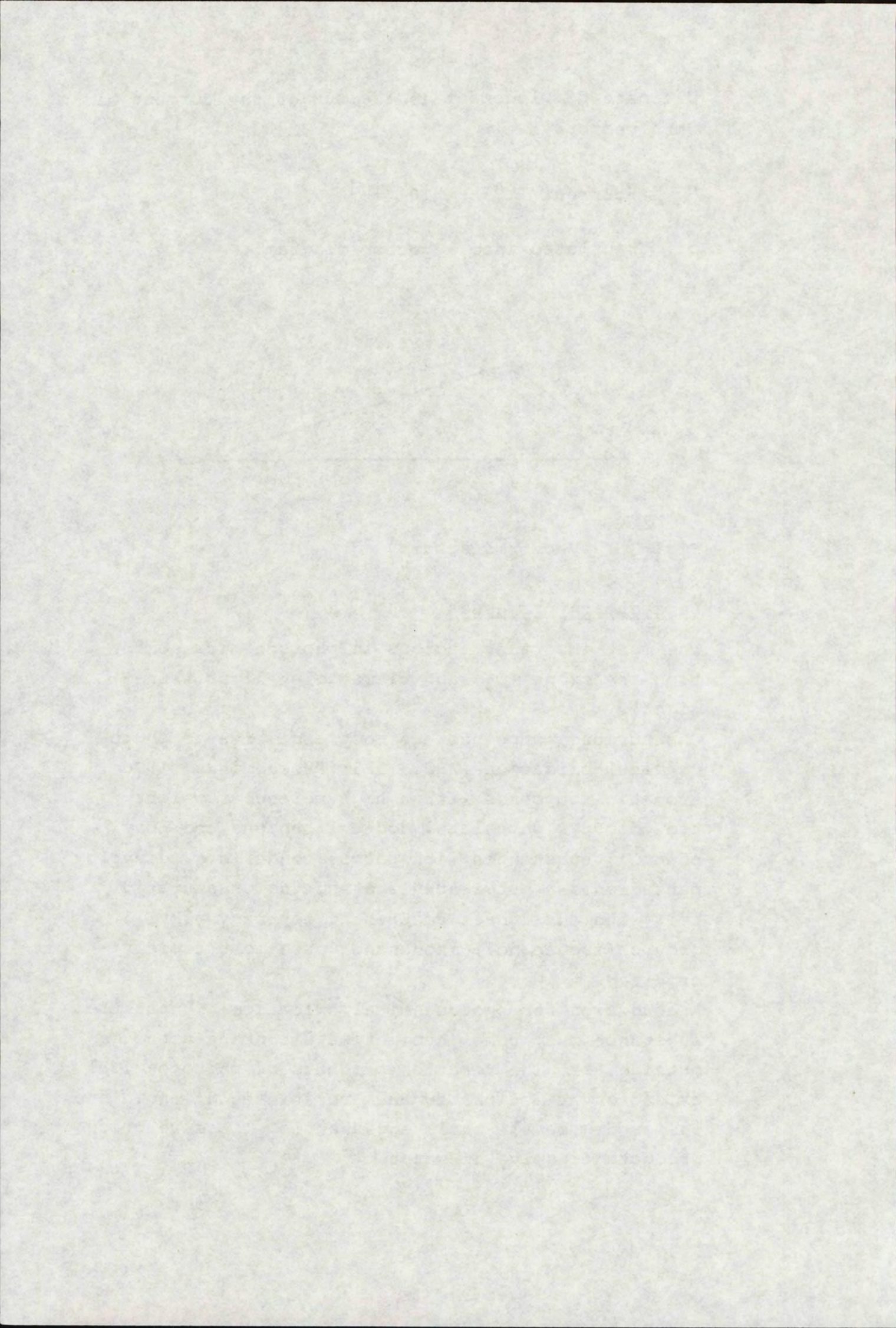
Fig. 7 Vector diagram

6.3 Degradation processes

The most important factors in photochemical oxidation are ozone (O_3) and ultraviolet light (sunlight).

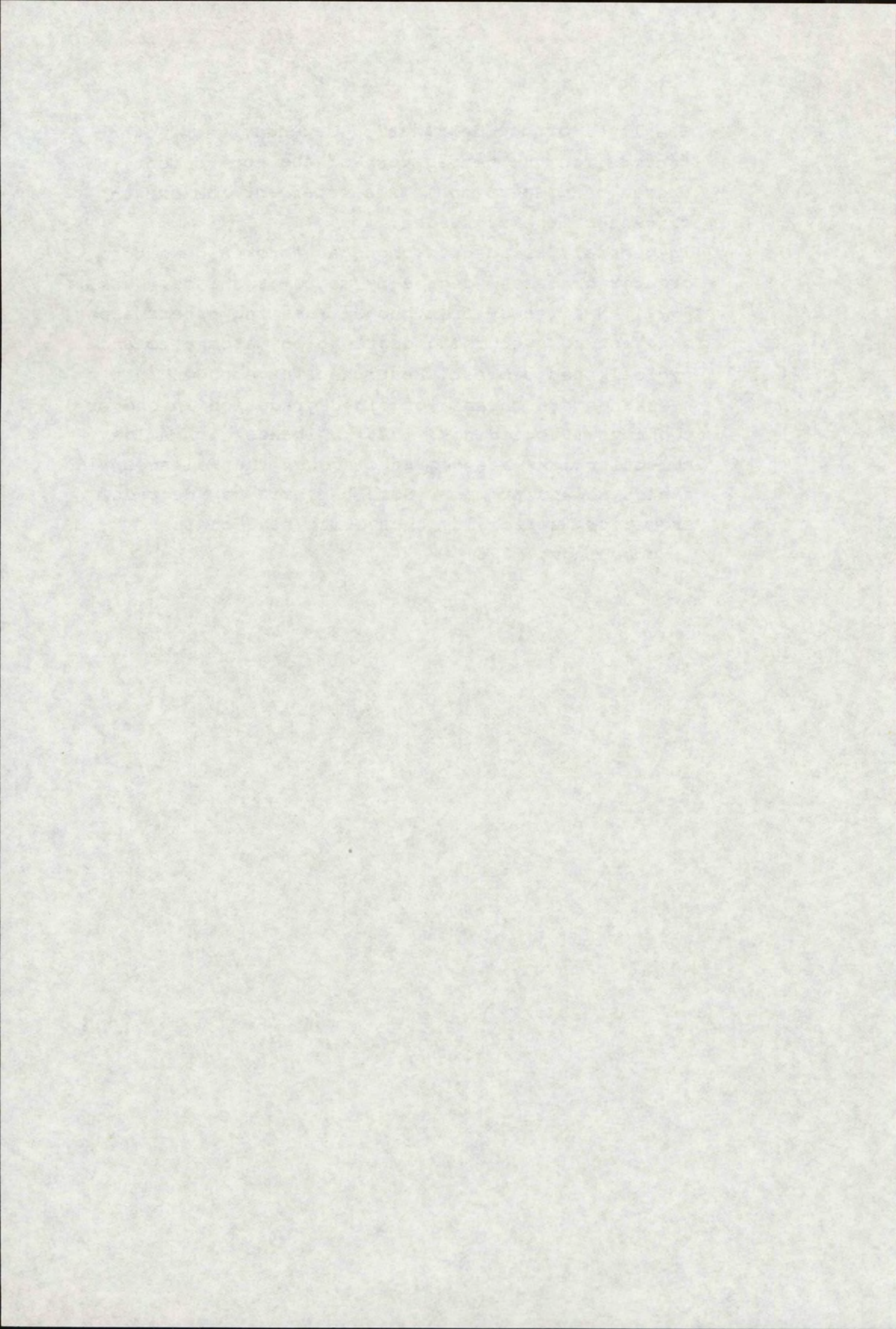
Unsaturated compounds are most sensitive to photochemical oxidation (WHO, 1978; Proceedings, 1976). Aromatic compounds with a high molecular weight e.g. dioctyl phthalate, dodecyl benzene and nonyl phenol), substances with double bonds (e.g. dicyclopentadiene, n-butyl acrylate and the unsaturated oils) and substances containing tertiary alkyl groups (isodecanol, isononanol) are most rapidly oxidized.

A condition for photochemical oxidation is that the substance must come into intimate contact with the outside air. The reaction products of photochemical oxidation are aliphatic and aromatic acids and, to a lesser degree, alcohols and phenols. These reaction products dissolve in water.



The level of bio-degradation depends, among other factors, on the temperature of the environment, the degree of dispersion in sea water and the oxygen content of the sea water.

In general, all hydrocarbons are broken down to a greater or lesser degree by micro-organisms (Dark, 1977). N-alkanes, branched alkanes and esters are quickest to succumb to degradation, aromatics and cycloalkanes slowest. Resarchers have shown that n-alkanes are capable of bio-degradation in one or two days (Proceedings, 1976). Alkanes with a low molecular mass are degraded sooner than alkanes with a high molecular mass. Some bacteria can degrade aromatics, especially those with side-chains (Proceedings, 1976).



7. Detection and identification of slicks

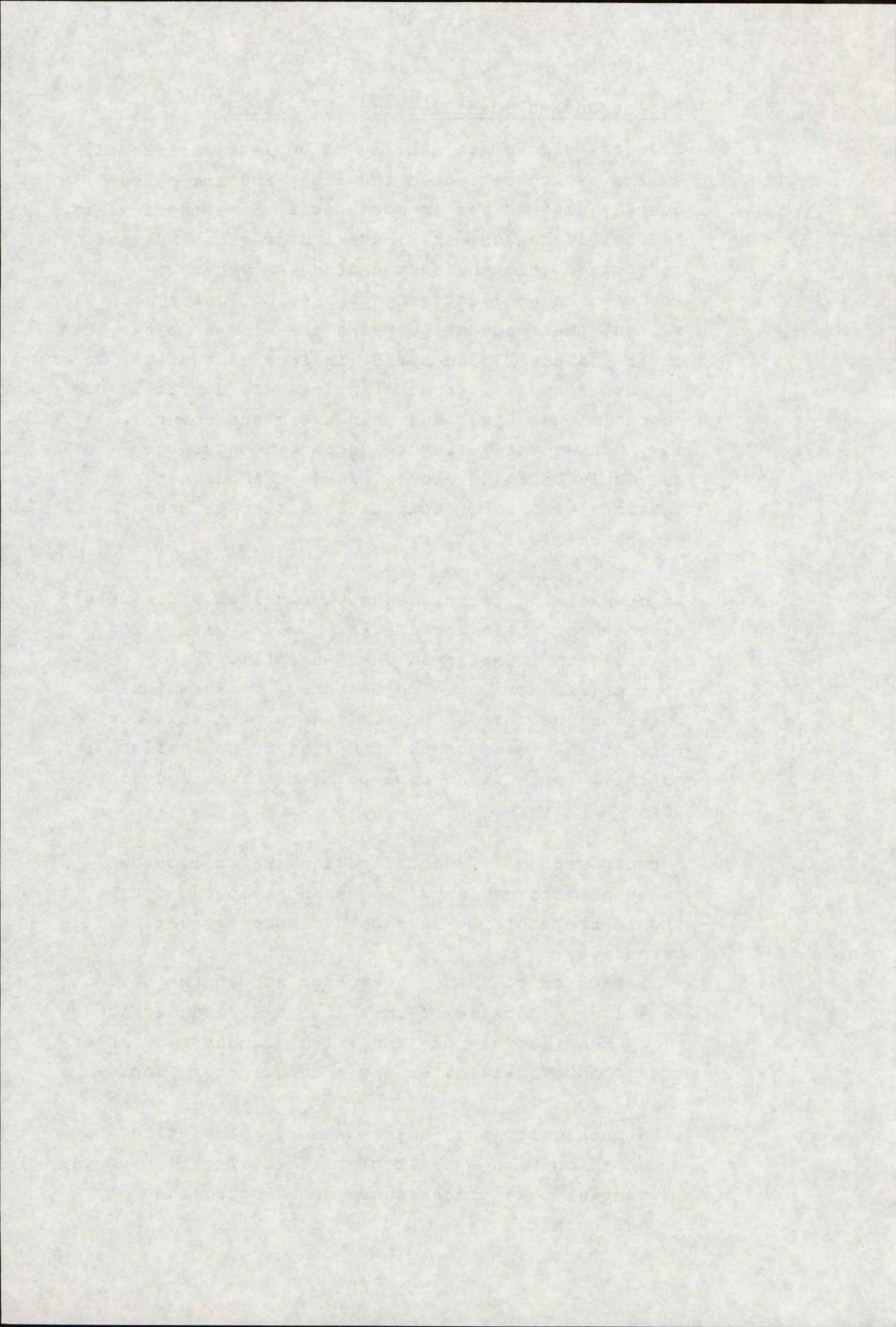
Chemical slicks are usually colourless, unlike oil slicks, which reflected the light and are consequently easy to see in most cases. Some chemical may be visible because they have a different index of refraction than the surrounding sea water.

Aircraft and helicopters are used to locate oil slicks, their advantage being the wide area they can cover and their high speed. Their disadvantage, on the other hand, is that sightings are difficult or impossible at night and when the cloud cover is low. Consequently, remote sensing methods are currently being developed. These methods can, possibly with some modification, also be used to detect chemical slicks.

Remote sensing techniques may be suitable for detecting and/or following slicks. However, it is not possible to identify an unknown spill. If appropriate action is to be taken, measurements must therefore be carried out in the spill itself. In view of the need for the findings to be available quickly, there is no time for extensive laboratory work.

A rapid method of identification, which provides relevant information within a short space of time, should therefore be developed. There are various alternatives:

- a package of instruments kept aboard the various ships. A package of this kind has been developed by EPA (for use on land). It includes a pH meter, a conductivity meter and a colorimeter (Bock, 1979);
- a package of instruments ashore. Samples have to be taken with a helicopter. Identification of the samples take place ashore or on board the helicopter.



8. Dangers of chemical slicks and appropriate act...

The potential dangers of slicks formed by substances from Main Group II may manifest themselves both above and below the surface of the water.

For example, the chemicals included in Sub-groups IIA and IIC will form both a slick and a vapour cloud, while substances in Sub-groups iIC and will form a slick and also a cloud of the react - products with water. The dangers and the action taken to eliminate them thus relate to:

- clouds above slicks: evaporation
- slicks
- clouds beneath slicks: reactions.

8.1 Evaporation

As a result of evaporation, the substances incl... in Sub-groups IIA and IIC will produce a cloud. The associated potential dangers of fire and explosions, and damage to human health, for example, are discussed in Chapter 5. A quantitative assessment of the evaporation process is to be found in Appendix

As Chapter 5 has shown, there are very few ways of dealing with gas and vapour clouds. It can even be said that the removal of a gaseous substance from the environment in the case of an accident is impossible. Consequently and in order to reduce the risks inherent in gas and vapour clouds, it is important to try to prevent the evaporation of a spill as far as possible.

The rate of evaporation can be reduced through the application of foam.

By spraying foam over an evaporating spill, the following effects are achieved:

- it becomes difficult for vapour to move away from the surface of the liquid;
- the heat from the sun is reduced, and less substance evaporates as a result;
- as one of the constituents of foam is water, a substance which dissolves in water is partly absorbed by the layer of foam.

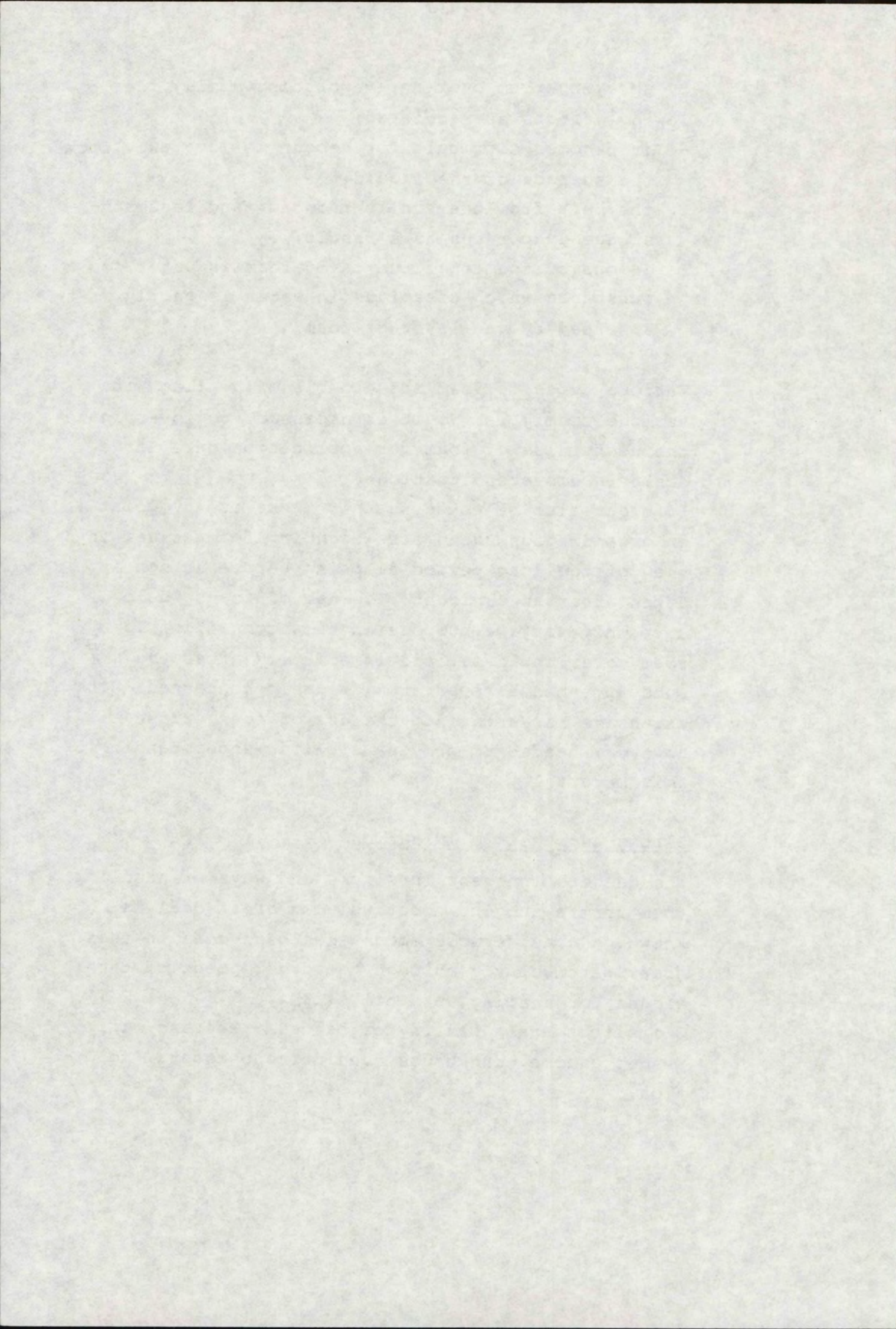
Various types of foam are capable of dealing with various chemicals. So it is necessary to investigate the usefulness of foam for application on a large scale in disastersituations.

It might also be asked whether there is any point in an organization using fire-fighting foam at sea in view of the long period elapsing before action is taken after an accident. The use of foams would certainly serve a purpose in this connection if a foam cover could be laid immediately after the substance had escaped from the ship concerned. More extensive research into the use of foams at sea is, however, needed to provide a better understanding of this material.

8.2 Slicks and their elimination

The dangers inherent in slicks and ways of handling them form a subject about which a great deal is known. A considerable amount has been done in this area, particularly through the development of techniques for dealing with oil slicks.

Oil slicks are a hazard for birds at sea and, if washed ashore, can cause considerable coastal pollution.



Action taken to deal with oil slicks is geared to the removal of the oil from the environment, this being achieved by mechanical means or, where they are unsuccessful, by adding chemical dispersants to dilute the oil in the water. Practically no experience has yet been gained with the appreciation of these various techniques of chemicals.

The overriding principle adopted is that, where pollution occurs, an attempt must be made to remove chemicals from the environment, particularly if they are xenobiotic. This may necessitate the adaptation of the present range of mechanical counter-pollution equipment. Where they cannot be adapted, new equipment should be developed. In addition, such chemical agents as gels, foams and absorbant materials could be used to collect the pollutant. None of these agents is, however, universally applicable (see Table 3), which means that, if the whole range of chemicals is to be covered, considerable investments must be made and logistical problems overcome. American studies have shown that effective materials do exist, but that they are very costly (Robinson, 1979). Furthermore, most of these materials have been developed for inland bodies of water rather than the open sea.

In order to prevent slicks spreading booms or waterjets can be used. Besides foams have been developed to encircle a slick (Friel, 1973). Further study is required in this area.

8.3 Substances which react with water and methods of containing them

Substances in Sub-groups IIC and IID will react with water beneath the spill that has formed. This may take the form of a physical reaction, e.g. the substance dissolves in the waer, or of a chemical reaction such as hydrolysis or decomposition.

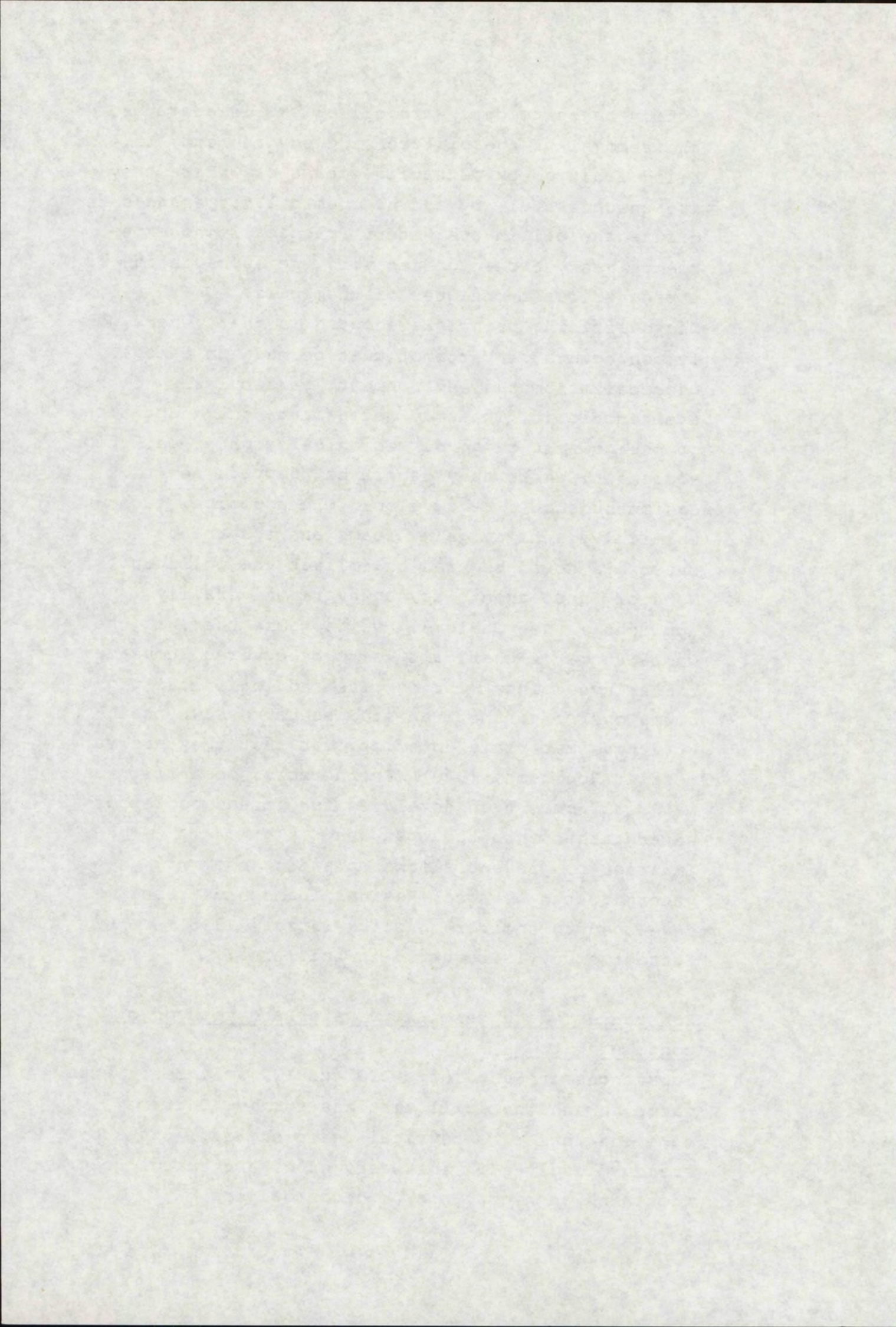


Table 3.

Compatibility of Hazardous Liquids and Selected Sorbent Materials																
HAZARDOUS LIQUIDS		SORBENT MATERIALS		Animal Materials ^a	Cellulose ^b	Cellulose ^c	Minerals ^d	Minerals ^e	Treated Minerals ^c	Polyolefins	Polypropylene ^c	Polypropylene ^c	Polyurethane ^c	Cross-linked Copolymer ^c	Multi-purpose Cellulose Agent ^c	
ORGANIC COMPOUNDS	HYDROCARBONS	Cyclohexane ^f				8										
		Isorene ^f														
		Benzene ^f			13 ^{h,k}		1	11		10 ^o		19,14				
		Ethylbenzene ^f														
		Styrene ^f														
		Toluene ^f					1	11								
		Xylene ^f					1	11								
	ACIDS AND DERIVATIVES	Acetic acid														
		Acetic anhydride														
		Butyric acid														
		Formic acid														
		Naphtheneic acid														
		Propionic acid														
		Propionic anhydride														
	ALCOHOLS	Allyl alcohol														
		Cresol														
		Phenol					1	15								
	ALDEHYDES AND KETONES	Acetaldehyde														
		Acrolein														
		Formaldehyde		x	x		1	9								
Furfural																
ESTERS	Amyl acetate ^f															
	Butyl acetate															
	Methyl methacrylate ^f															
	Pyrethrins															
	Vinyl acetate															
HALOGEN COMPOUNDS	Acetyl bromide															
	Acetyl chloride															
	Allyl chloride ^f															
	Chloroform															
	Cyanogen chloride															
	Phosgene															
	Benzoyl chloride															
	Benzyl chloride															
	Chlordane															
	Chlorobenzene															
	Polychlorinated biphenyls															
	NITROGEN COMPOUNDS	Acetone cyanohydrin														
Acrylonitrile							1	10								
Butylamine																
Diethylamine																
Dimethylamine																
Ethylenediamine																
Hydrogen cyanide																
Monoethylamine																
Triethylamine																
Aniline																
Benzonitrile																
Nitrobenzene																
Quinoline																
Trimethylamine																
SULFUR COMPOUNDS		Carbon disulfide														
	Chlorosulfonic acid															

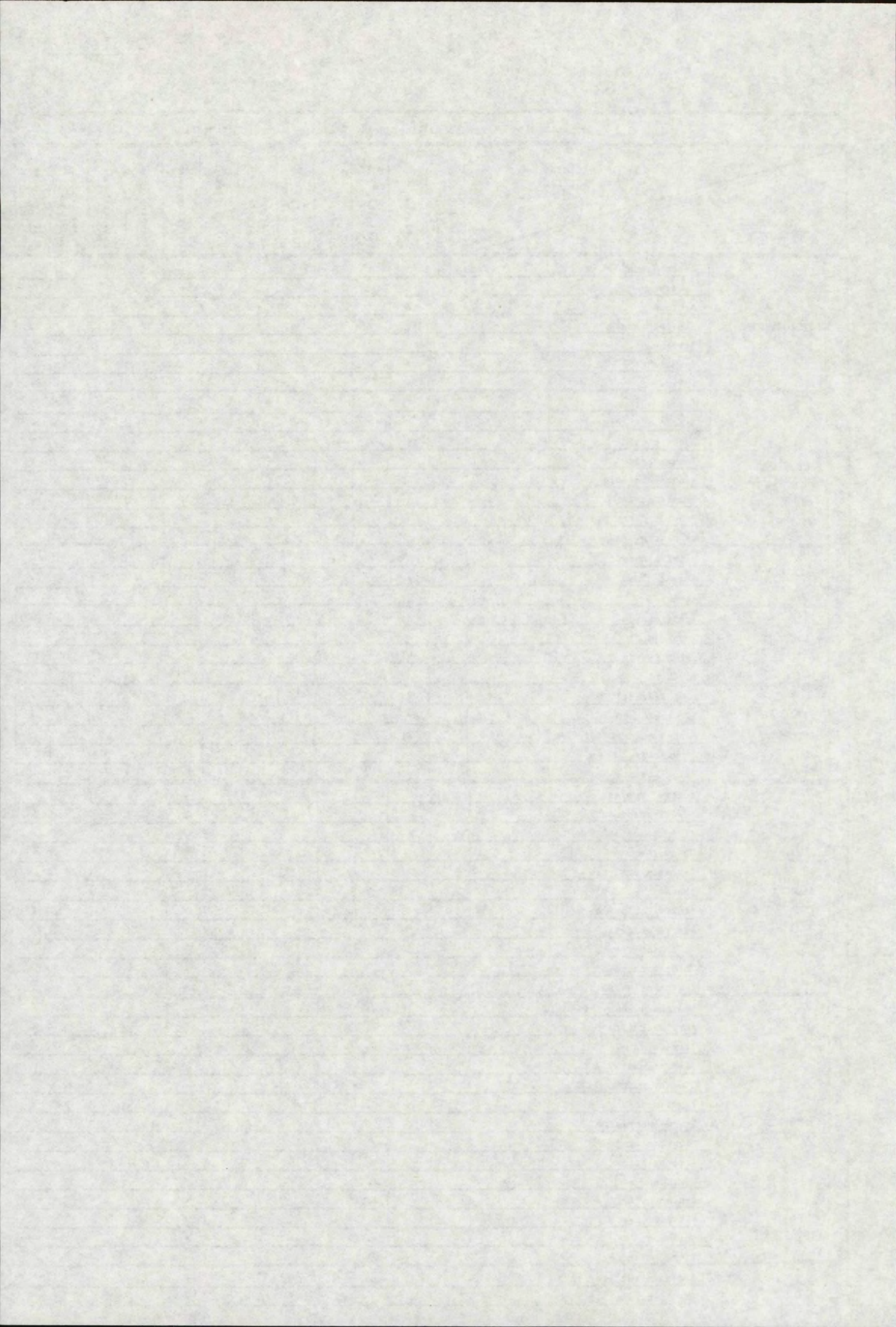


Table 3- (contd)

Compatibility of Hazardous Liquids and Selected Sorbent Materials (Contd)														
HAZARDOUS LIQUIDS		SORBENT MATERIALS												
		Animal Materials ^a	Cellulose ^b	Cellulose ^c	Minerals ^d	Minerals ^e	Treated Minerals ^c	Polyolefins	Polypropylene ^c	Polypropylene ^c	Polyurethanes ^c	Cross-linked Copolymer ^f	Multi-purpose Gelling Agent ^g	
ORGANIC COMPOUNDS	ORGANOPHOSPHORUS COMPOUNDS	Diazinon							✓					
		Dichlorvos							✓					
		Disulfoton							✓					
		Ethion							✓					
		Malathion			✓				✓					
		Methyl parathion					✓						✓	
		Mevinphos							✓					
		Malid							✓					
		Parathion					✓		✓				✓	
		Tetraethyl pyrophosphate												
INORGANIC COMPOUNDS	ACIDS	Tetraethyl lead			✓		✓		✓					
		Hydrochloric acid	x	x	x	✓	✓		✓					
		Hydrofluoric acid	x	x	x	✓	✓							
		Nitric acid	x	x	x	✓	2	20	✓					
		Phosphoric acid	x	x	x	✓	2	23	✓					
	INORGANIC HALIDES	Sulfuric acid	x	x	x	✓	2	19	✓				✓	
		Antimony pentachloride												
		Arsenic trichloride							✓					
		Phosphorus oxychloride				✓			✓					
		Phosphorus trichloride				✓			✓					
Sodium hypochlorite (solution)														
Sulfur monochloride								✓						
OTHER	Zinc chloride (solution)													
	Ammonium hydroxide											✓		
		Nitrogen dioxide			✓									
ADDITIONAL INFORMATION			k	l	k	3.0	a	k	l	k	k	o	3.0	

Reference: John E. Brugger
Proceedings 1980.

Explanation.

- a Wool, feathers, chrome, leather shavings
- b Straw, sawdust, bark, hulls, peat moss
- c Includes proprietary product(s)
- d Calcium carbonate
- e Ash, sand, vermiculite, perlite, clays
- f Insoluble floater
- g "✓" represents compatible combinations
- h Numbers represent absorption capacity (mass of material sorbed per unit mass of sorbent); based on experimental data
- i Conclusion based on experimental data, rather than extrapolation or speculation
- j "x" represents incompatible combinations
- k Bauer, W.M., et al., (1975), Agents, Methods and Devices for Amelioration of Discharges of Hazardous Chemicals on Water, U.S. Coast Guard, Washington, DC
- l Data sheet on proprietary product
- m Pilie, R.J., et al., (1975), Methods to Treat, Control and Monitor Spilled Hazardous Materials, EPA-670/2-75-042
- n Temple, R.E., et al., (1978), A New Universal Sorbent for Hazardous Spills, In *Proceedings of the 1978 National Conference on the Control of Hazardous Material Spills*, U.S. EPA (available from Information Transfer, Inc., Rockville, MD)
- o Akers, C.K., et al., Guidelines for the Use of Chemicals in Removing Hazardous Substance Discharges, U.S. EPA Contract No. 68-03-2093 (in preparation)
- p Micanovic, J.G., et al., (1977), Multipurpose Gelling Agent and Its Application to Spilled Hazardous Materials, EPA-600/2-77-151

Fig. 8 gives a general impression of the solubility of hydrocarbons.

The reaction products will form clouds in water. The behaviour and counter pollution actions of these clouds are similar to cloud formed by substances from Main Group III. For this reason the discussion of the various aspects will take place in the Chapters 9 to 11.

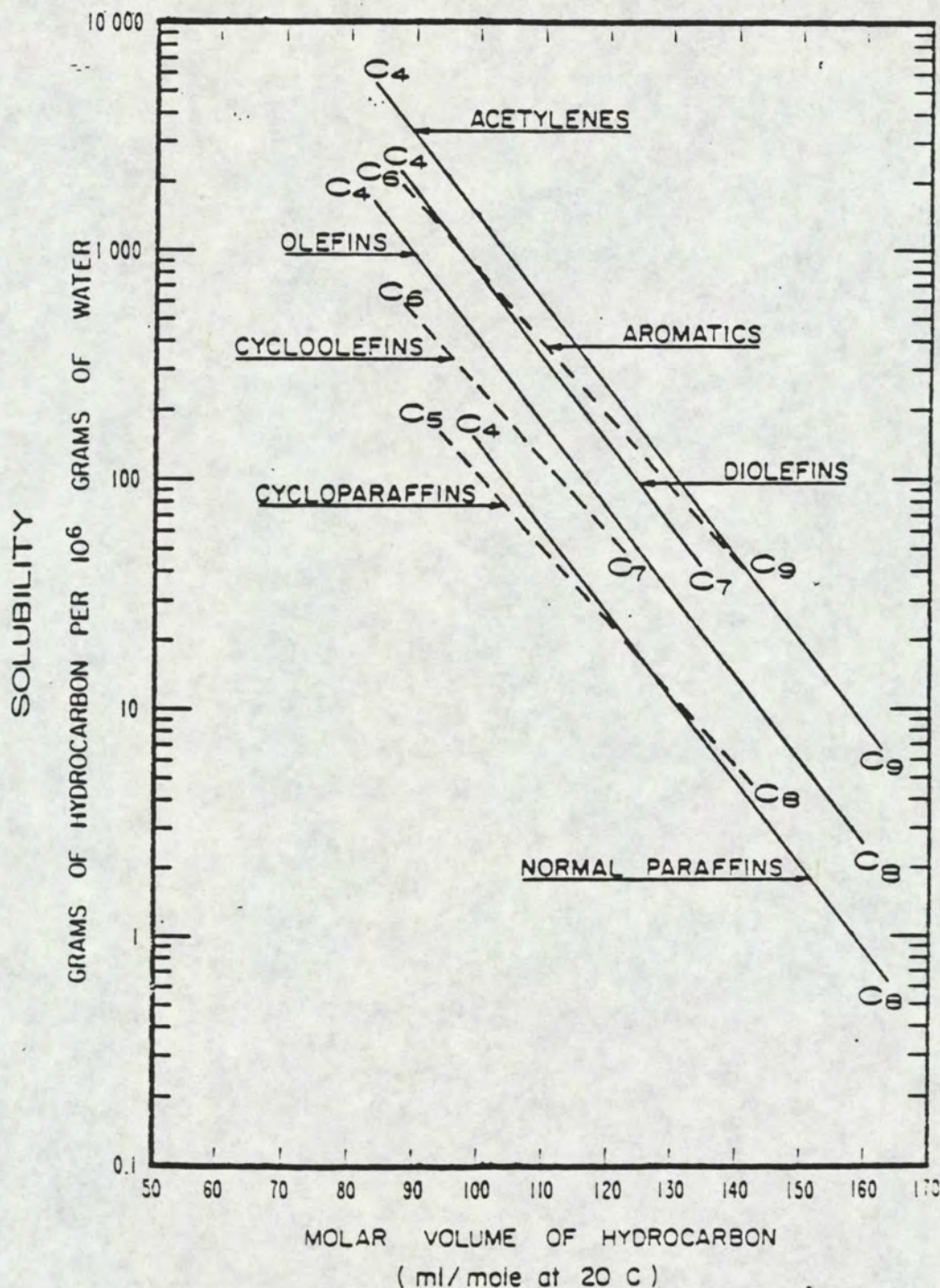
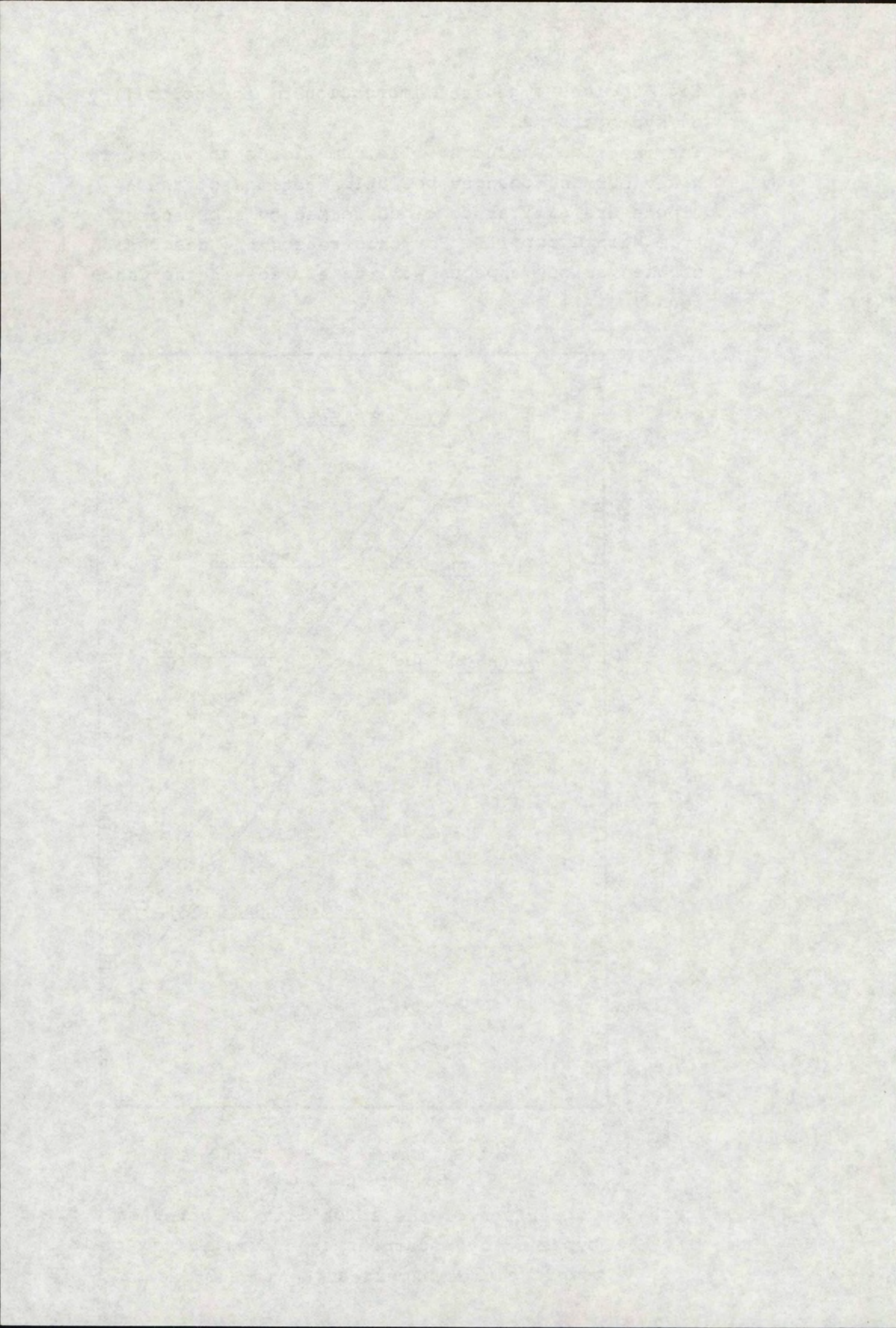


Figure 8. Comparison of the solubility in water of various types of hydrocarbons as a function of their molar volumes (American Petroleum Institute 1969)

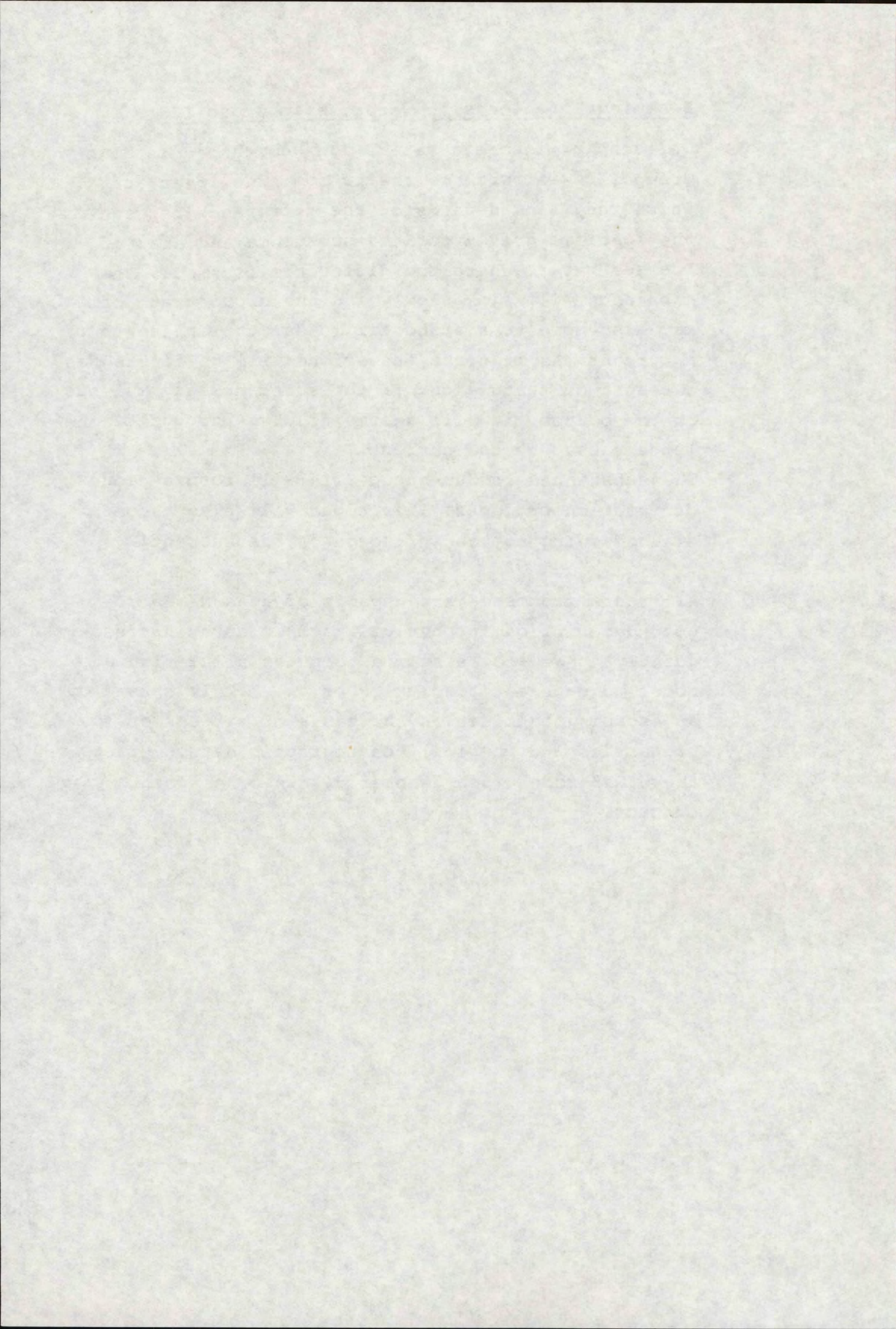


9. Behaviour of clouds in water: Main Group III

On escaping into sea water, the substances in Main Group III will sink to the bottom. The speed at which they sink depends on the difference between the specific gravity of the substance and that of the sea water. Where the difference is small, the substance will sink slowly and the cloud that forms may also come to a standstill under the influence of a current. As it sinks, the cloud will be diluted as a result of turbulence. If the substance accumulates on the bottom, it will become diluted through turbulence caused by the current.

The substances in Sub-group IIIA will form a cloud of reaction products. This cloud will also become diluted owing to the influence of the current.

All these processes are capable of reasonable to good description in physical terms. There is consequently a need for a simple computer simulation model to enable a prediction of the likely spread of an escaping chemical on the basis of various of its properties and physical oceanographic data. Perhaps the CHRIS model (see Chapter 3) can offer points of contact.



10. Detection of clouds in water and accumulations on the bottom .

Pollutants which have sunk beneath the surface are often difficult to detect until effects such as dead fish indicate their presence.

To limit the damage to the environment, the pollutant must be detected as soon as possible and the extent of the pollution determined.

10.1 Detection using the conductivity of the substance

The conductivity of organic chemicals which sink is generally many times lower than that of sea water (sea water: $43 \times 10^{-3} \text{ mho cm}^{-1} \text{ gr}^{-1}$, as against CCl_4 : $4 \times 10^{-8} \text{ mho cm}^{-1} \text{ gr}^{-1}$).

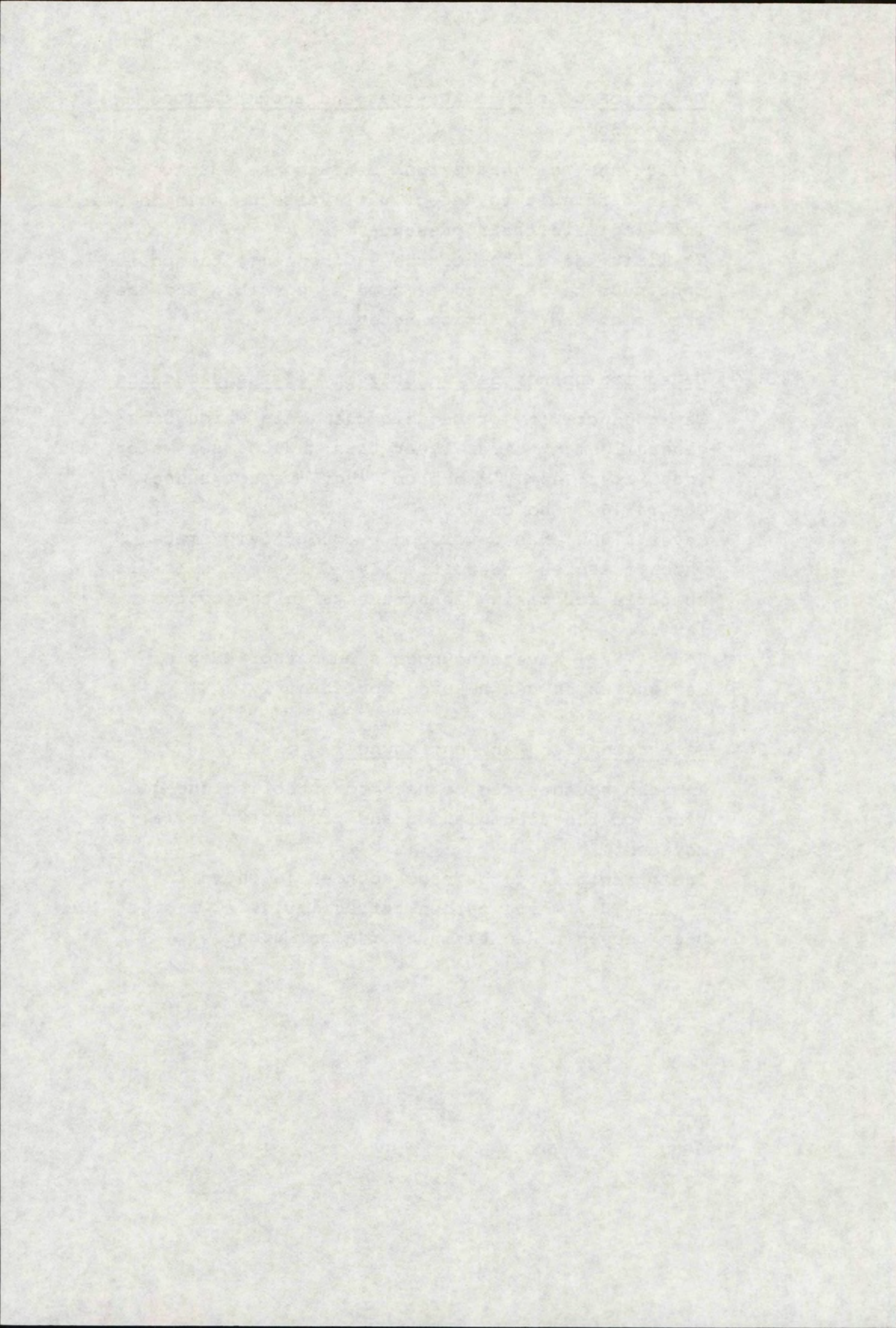
Meyer (1980) has developed a conductivity meter, which measures intermittently. This design is also suitable for taking measurements in the bottom layer.

Bock (1979) have announced a number of simple designs which can be used continuously.

10.2' Detection using an echo sounder

An echo sounder can be used to establish the dimensions of the accumulation and its behaviour (e.g. movement)

The principle of the echo sounder is shown in Figs. 9 and 10 , where carbon tetrachloride (CCl_4) has been chosen as an example of a pollutant.



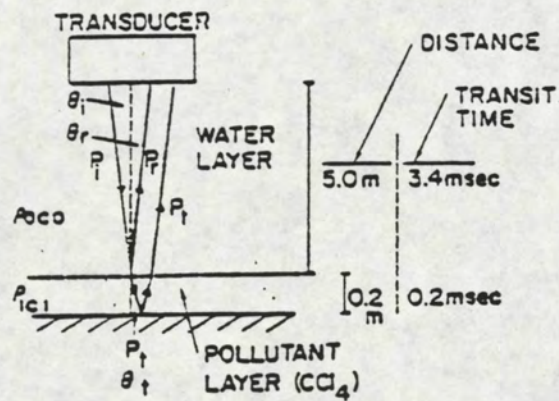


Fig. 9 : diagram showing an echo sounder being used to locate an accumulation of CCl_4 . (Meyer, 1980).

P_i = initial wave
 P_r = reflected wave
 P_t = transient wave.

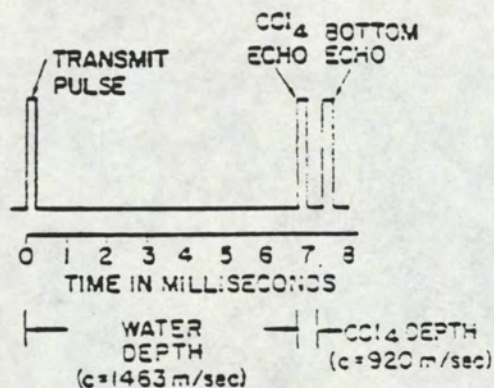


Fig. 10 : signal strength as a function of time during measurements under the conditions of Fig. 9 (Meyer, 1980).

An echo sounder with a frequency of 200 kHz produces a satisfactory signal in water.

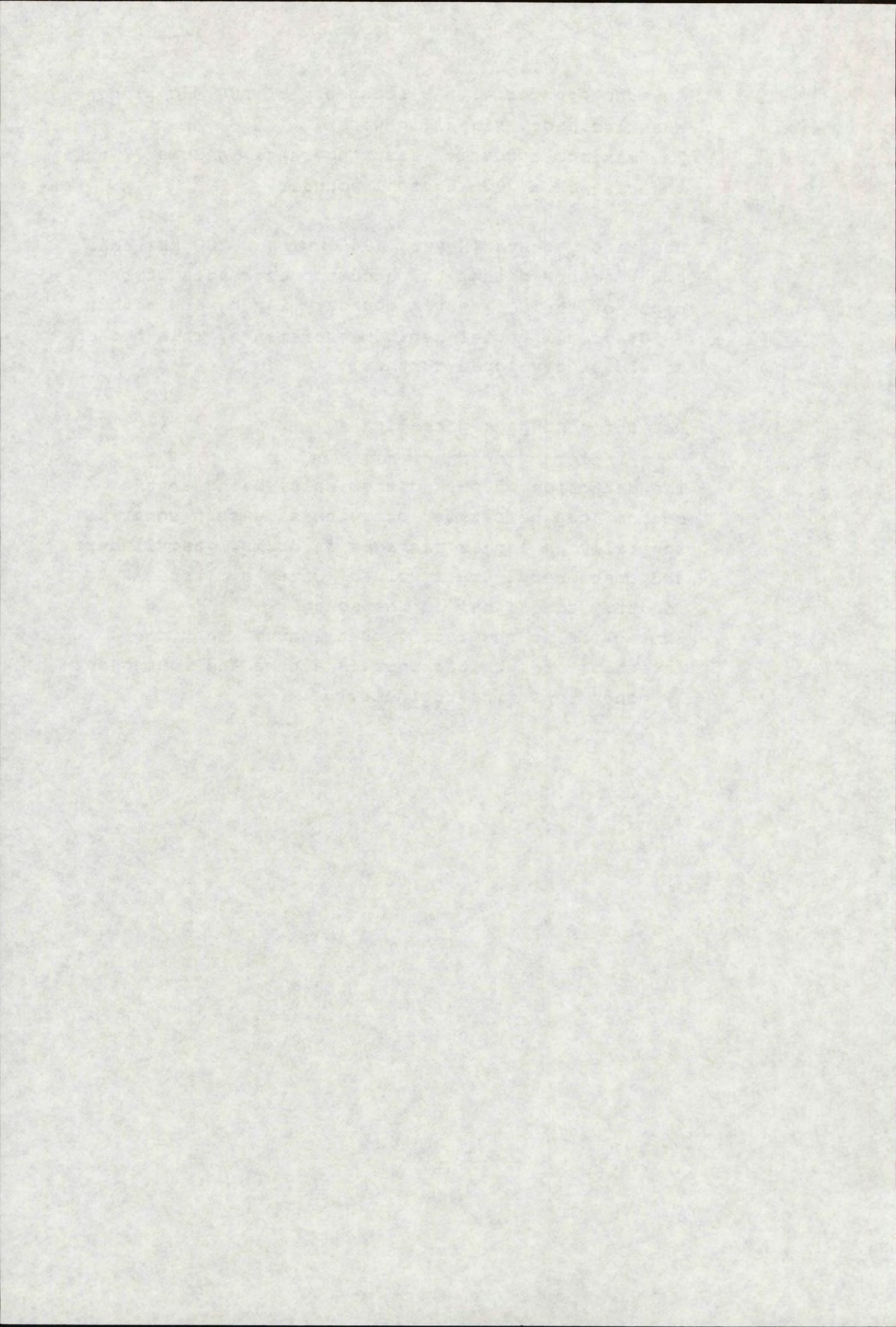
The maximum acoustic measuring range is some 73 m in the case of a 200 kHz echo sounder.

Laboratory tests (Meyer, 1980) with a 200 kHz echo sounder showed that the acoustic estimates of the depth of the CCl₄-water boundary layer were within $\pm 20\%$ of all actual depth measurements. This method should be developed further.

10.3 Detection of packed chemicals

The detection of packed chemicals, being on the bottom, can be carried out with side scan sonar, specially as larger packages as drums, gas cylinders and containers, are involved. Often a diver has to identify the signal of the sonar.

Some cases in the recent past learned that the detection of such packages is a time and consequently money consuming business.



11.1 Counter pollution activities of pools on the seabed

There are various ways of dealing with pools on the seabed:

- causing a reaction
- burying
- removal with dredgers
- a combination of these methods.

11.1.1 Causing a reaction

By adding an agent to a cloud, whether or not it is sinking, the original substance can be converted into a less harmful substance or into a substance which sinks. The disadvantage of this method is that large quantities of a specific agent are required.

No experience has yet been gained with the use of sorbents, gels and foams on sinking clouds at sea. It is not known what effect the pressure at greater depths has on the activity of these agents.

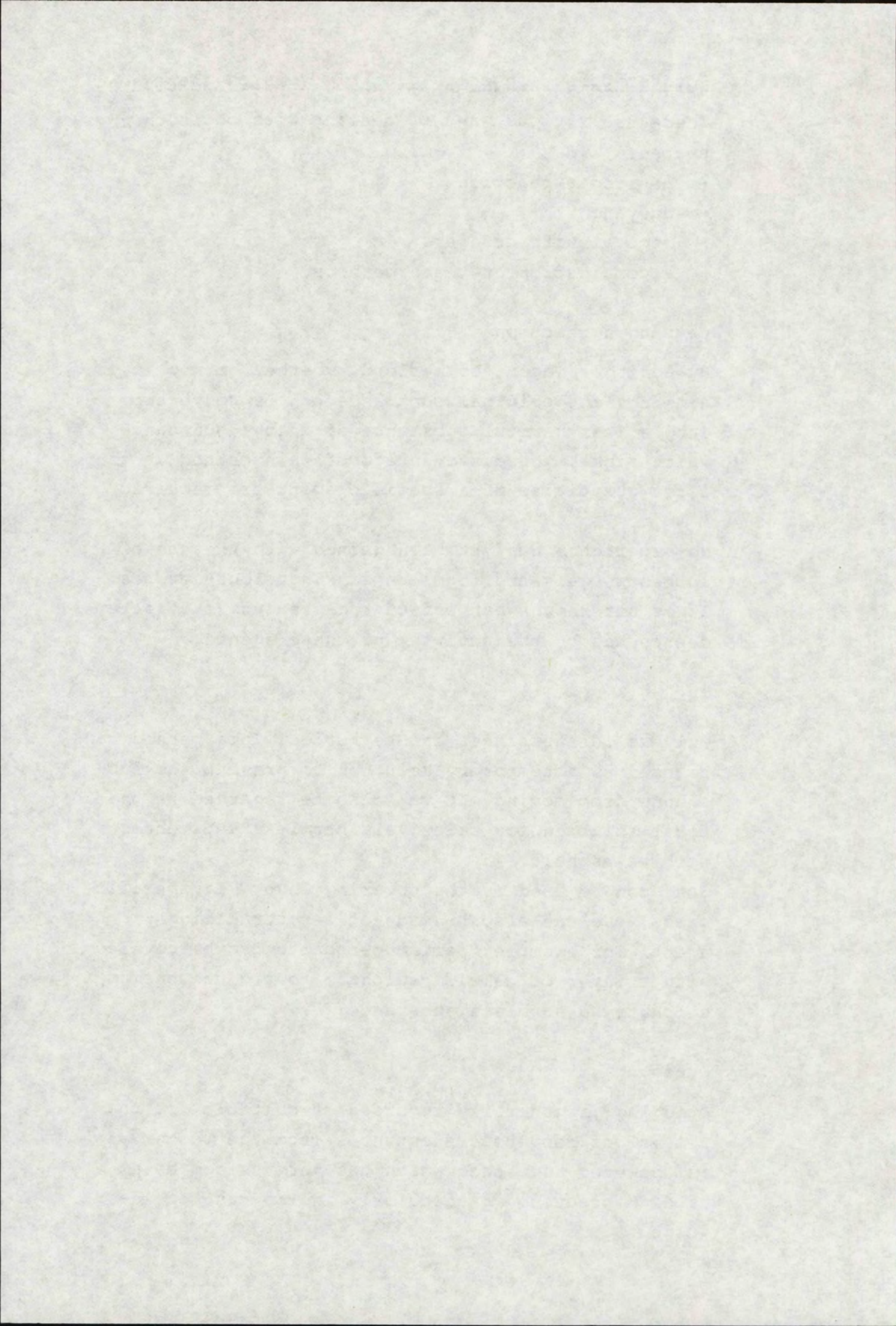
11.1.2 Burying

Only solid substances can be buried. This method can be used as a temporary solution to prevent the substance from moving. It can also be regarded as the final solution for relatively harmless substances such as asphalt.

Sand can be used as the covering layer. In specific cases, use can also be made of a neutralizing agent. For example, barium carbonate can be covered with a layer of calcium sulphate to produce barium sulphate, a harmless substance.

11.1.3 Dredging

Dredging is generally regarded as suitable for the removal of dangerous substances from the bottom. It is, however, a method which has very seldom been used in practice, particularly in the case of liquids.



There are three dredging methods:

- mechanical systems:
the use of buckets, pinchers or cutters
- hydraulic systems:
a hydraulically driven centrifugal pump creates a vacuum
- pneumatic suction systems:
a vacuum is created with the aid of a compressor and air chambers.

Mechanical dredging seems less suitable for collecting toxic pollutants, since it increases turbulence in the water and churns up the bottom. This may result in the dispersion of a major portion of the pollutant in the water thus enlarging the danger zone, which may cause even greater damage to the marine environment. However, new types of cutters are currently being developed, the object being to reduce the turbulence around the cutter and so prevent fresh material from the sea bed from becoming suspended in the water.

An added factor is that few mechanical systems are suitable for use on the open sea.

Of the hydraulic systems the trailer suction hopper dredge would seem to be the most suitable in this context. The sea-going types can be used anywhere. Their disadvantages are that they can work only up to a depth of some 35 m and that the capacity of the hopper is limited.

Consideration might be given to the use of ships as is now done with the "Cosmos" to deal with oil pollution.

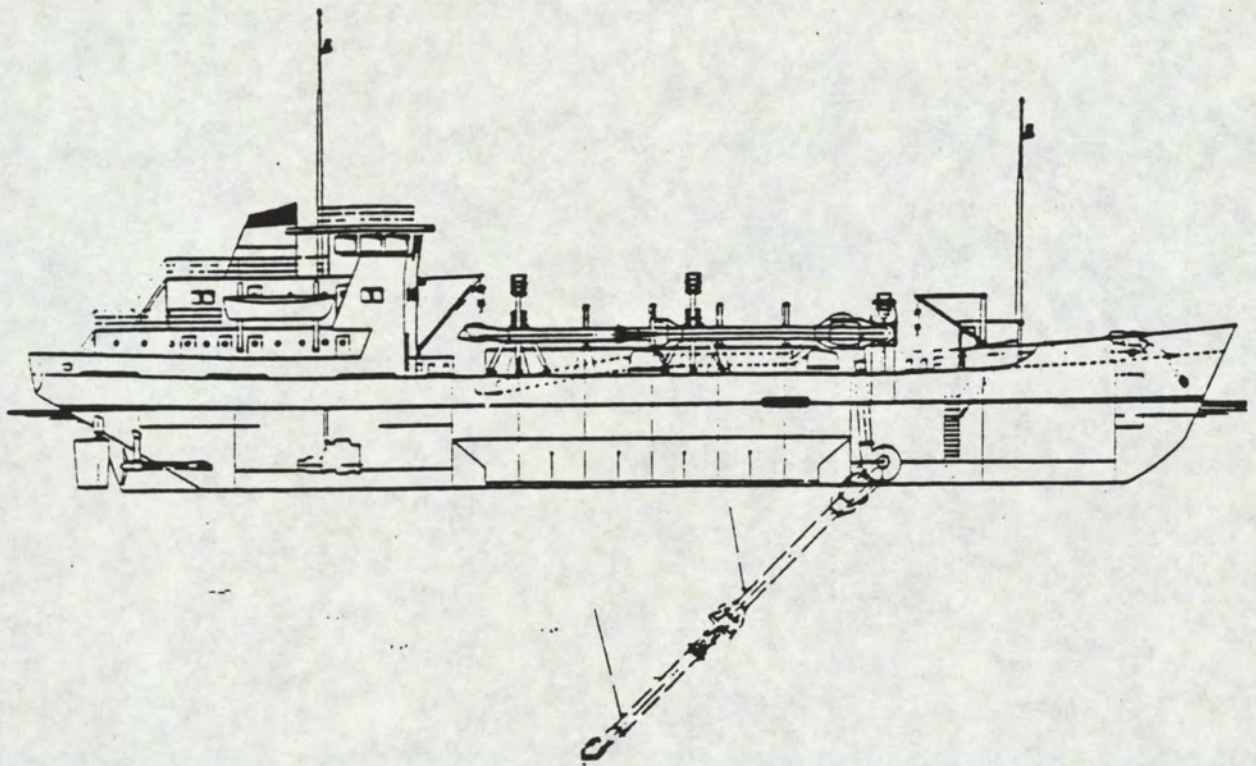


Fig. 12: Trailer suction hopper dredge (PIANC, 1977).

The pneumatic suction systems are the most recent development in the field of dredging. In Italy and Japan in particular various systems have been developed to remove layers of pollutant sludge. Turbulence is minimal with these systems. Their use is generally independent on the depth of the water.

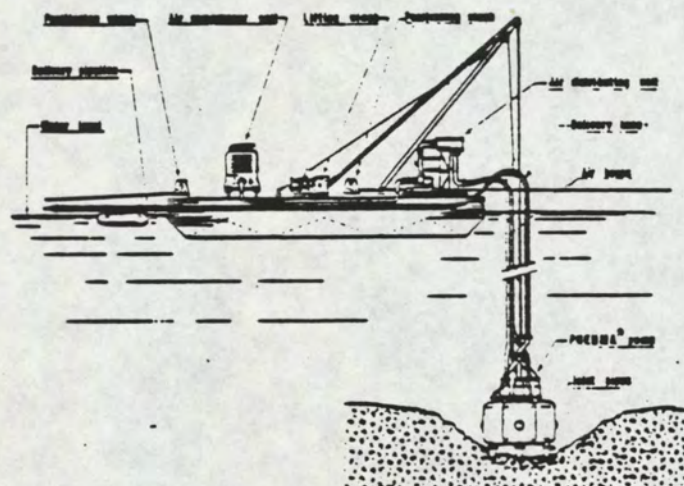


Fig. 13: Pneumatic system (PIANC, 1977).

A study should be made to establish what dredging equipment is available or could be used in the Netherlands for the removal of pollutants. Account should also be taken in this study of other developments such as deep-well pumps and emergency discharge systems.

11.2 Counter pollution activities of clouds in water

In recent years many agents have been developed to combat pollutants in water. Only a limited number have proved successful, and even then their use is confined to small accidents, either on inland waterways or on land (Robinson, 1979).

The various methods on which these agents are based are:

- absorption
- solvent extraction
- neutralization
- precipitation
- chelate formation.

Where sorbents are used, it is important for there to be a high concentration of the chemical concerned. Such high concentrations will usually occur in sea water. Solvent extraction is suitable for only a small number of chemicals and requires a great deal of equipment.

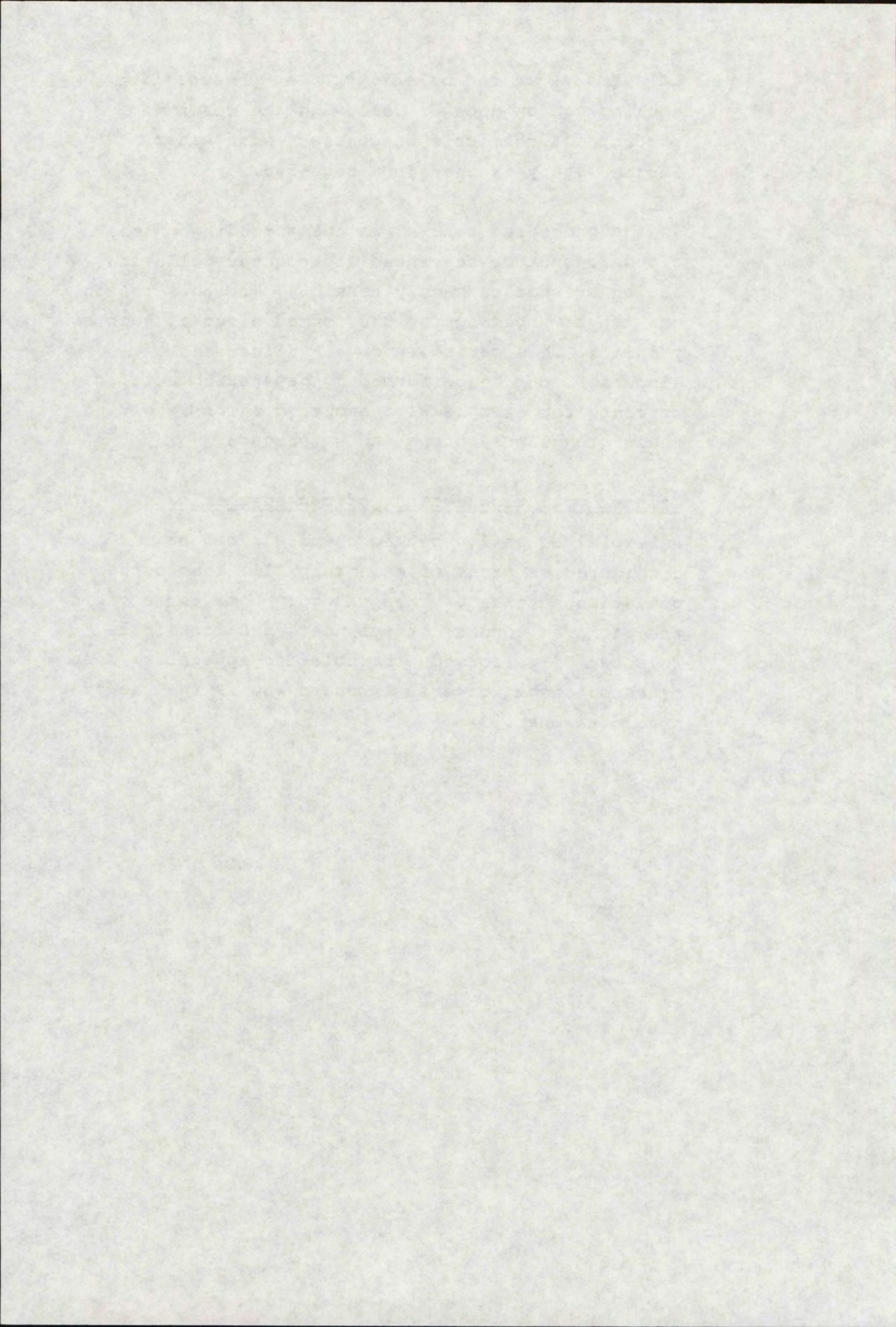
In the case of the last three methods listed above, a specific reagent is needed for each pollutant. This conflicts with the aim of developing uniform methods.

In summary, it can be said that at present little or nothing can be done to deal with the reaction products of chemicals which react with water. Further study is therefore required.

As the preceding text shows the spreading of the clouds cannot be prevented and counter pollution action are not of hardly feasible. For this reason one can try to disperse the formed cloud as soon as possible. This method, know as "dilute and disperse", can be performed by generating artificial current, for example with anchored ships revolving their propellers, pumps and water gets.

11.3 Counter pollution actions of packed chemicals

As explained in 2.4 packed chemicals can be considered as parts of Maingroup III. The counter pollution actions of this category come to salvaging the packages: drums, gascylinders and containers. This can be performed with hoisting-apparatus. That means putting on divers. An other way is the use of a steel trawl-net.



12. Conclusions and recommendations

The substances escaping during a calamity with chemical tankers will spread: in the air, on the water surface, in the water itself and on the bottom. The distribution of the substances over these locations depends on the properties of the substances concerned.

Based on these properties, chemicals can be classified as follows:

- I substances, forming gas and vapour clouds
- II substances, which float on the water
- III substances, which sink or are suspended.

It appeared that for transport of chemicals these names or categories are used, such as: brake fluid, H/C solvent, etc. It is recommended to arrive at standardized names on the bills of lading, for example based on U.N. numbers.

Behaviour:

The substances from Main Group I are practically all heavier than air. No calculation model for the diffusion of this category of gases and vapours is available in the Netherlands at the moment. It is desirable to develop such a model in the near future.

For the diffusion of 'clouds' in water there is no integrated calculation model available either, such a model needs to be developed too.

Detection

The application of remote sensing techniques for the detection of gas and vapour clouds and of slicks seems feasible.

However, a study of the usefulness of the equipment available at present is desirable.

The use of planes for direct measurements in gas and vapour clouds should be investigated in more detail. In addition to detection, for slicks of unknown composition, there is also a need for identification of the substances concerned. This means that further research must be done into the possibilities of quick analyses, either ashore or at sea.

For the detection of clouds in water a number of techniques are given: by means of conductivity measurement or by echo sounders. Both methods should be further developed on the basis of practical tests.

Hazards and their abatement

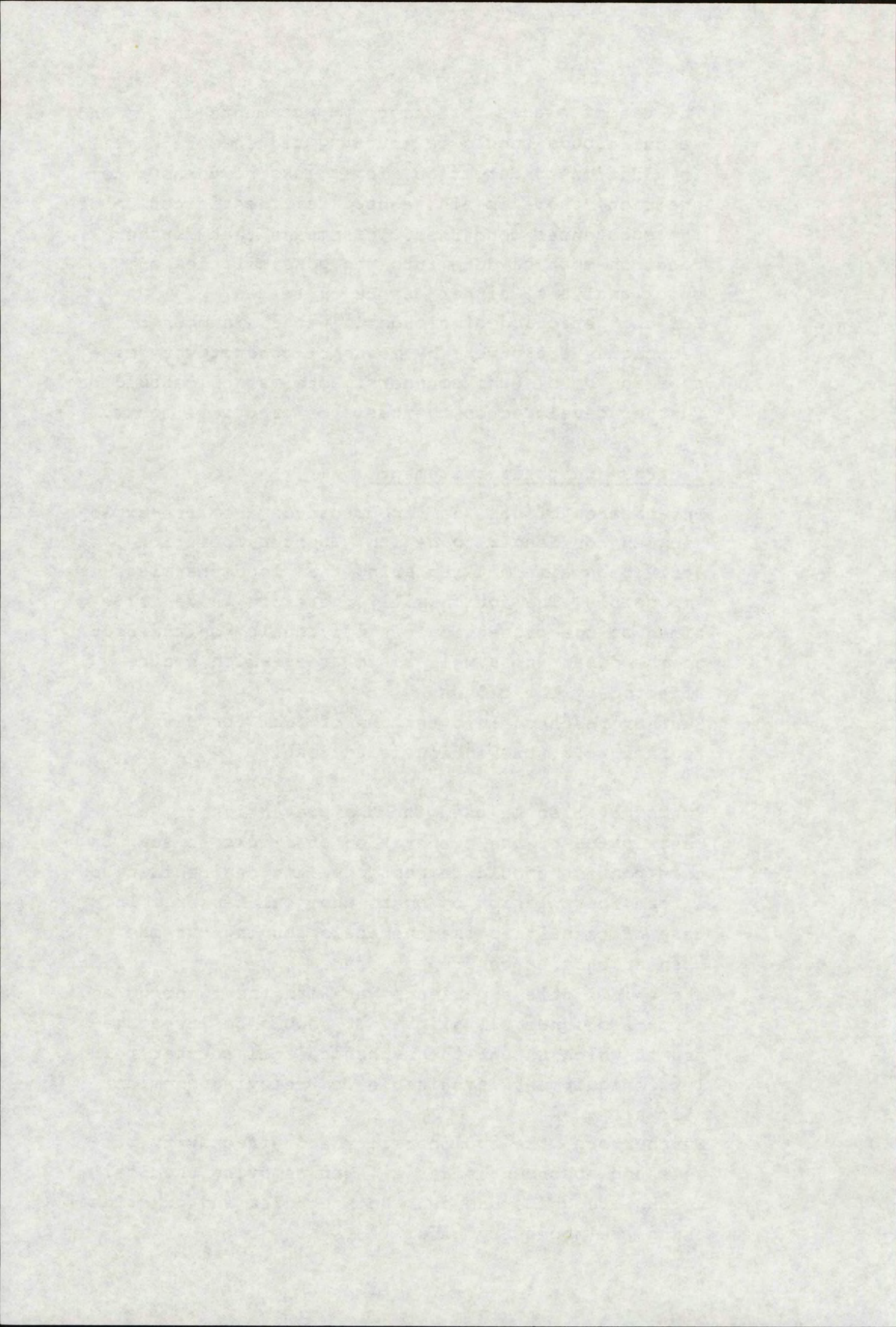
The hazards of gas and vapour clouds are fire-explosion and/or danger to health. Counter pollution activities aimed at rendering the clouds harmless is impossible. The action will, therefore, have to be aimed at the protection of individuals, on the spot of the disaster as well as in areas which can be affected by the clouds.

Further research into the use of foam for fire fighting c.q. prevention is advisable.

Foams may also be used for the prevention or restriction of the evaporation of slicks at sea. In this context should be mentioned the desirability of a foam installation on board chemical tankers. In case of casualties the chemicals pouring out may then at once be covered by foam.

There is little experience yet with the fighting and control of chemical slicks. It should be investigated to which extent the mechanical oil counter pollution equipment is suitable for removing chemical slicks.

Furthermore, the applicability and effectivity of gels and absorbant material, for removing chemical slicks are quite unknown. Both studies and practical tests are necessary here.



The counter pollution of clouds of chemicals in water seems impossible.

In order to restrict the damage we will have to try to quickly reach a low concentration by artificial dilution.

For the abatement of pools on the ground should be aimed at limiting their size in the first place. Actions to make pools harmless are e.g. chemical reagents, burying and dredging.

In particular the latter technique should be further investigated on its operational benefits.

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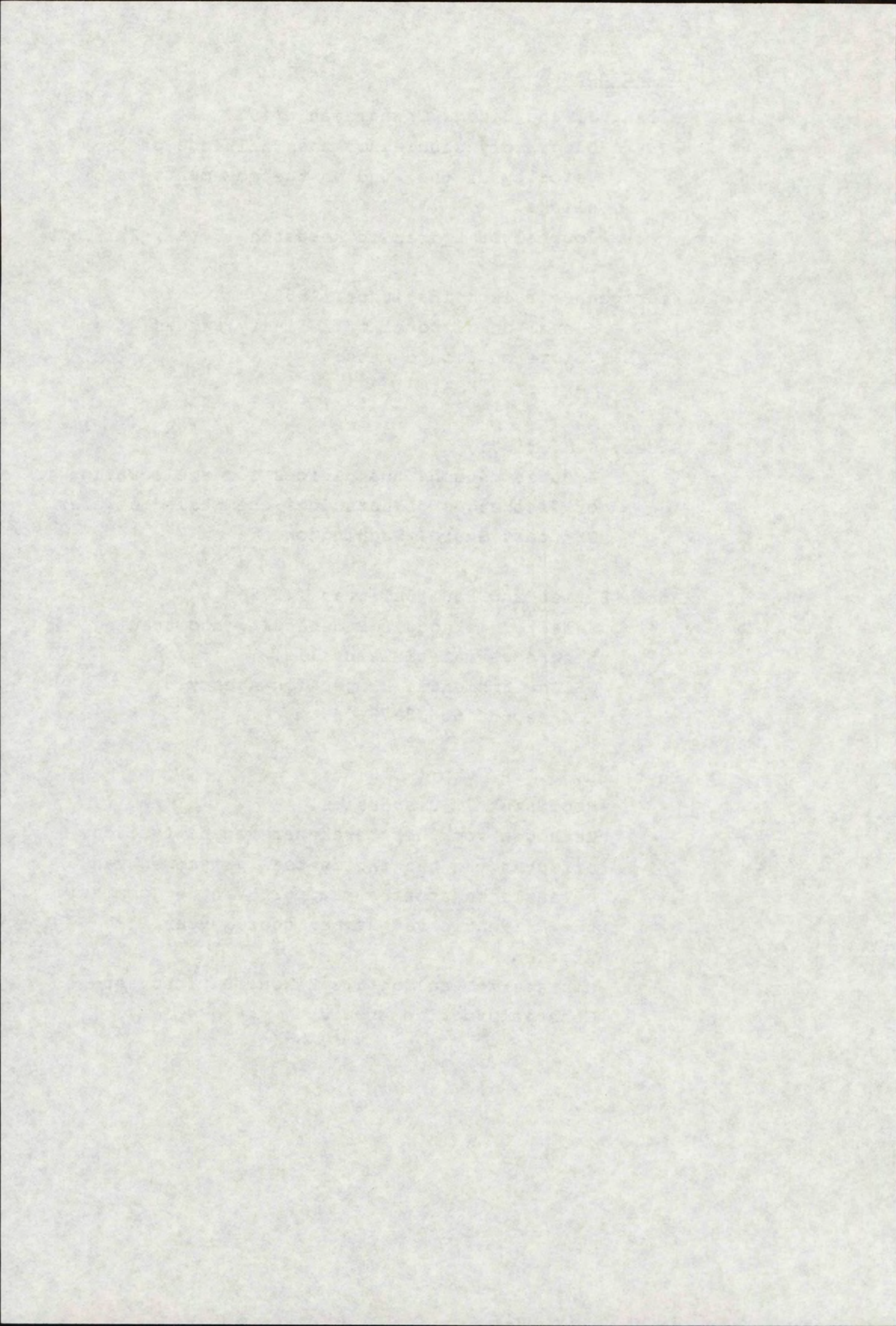
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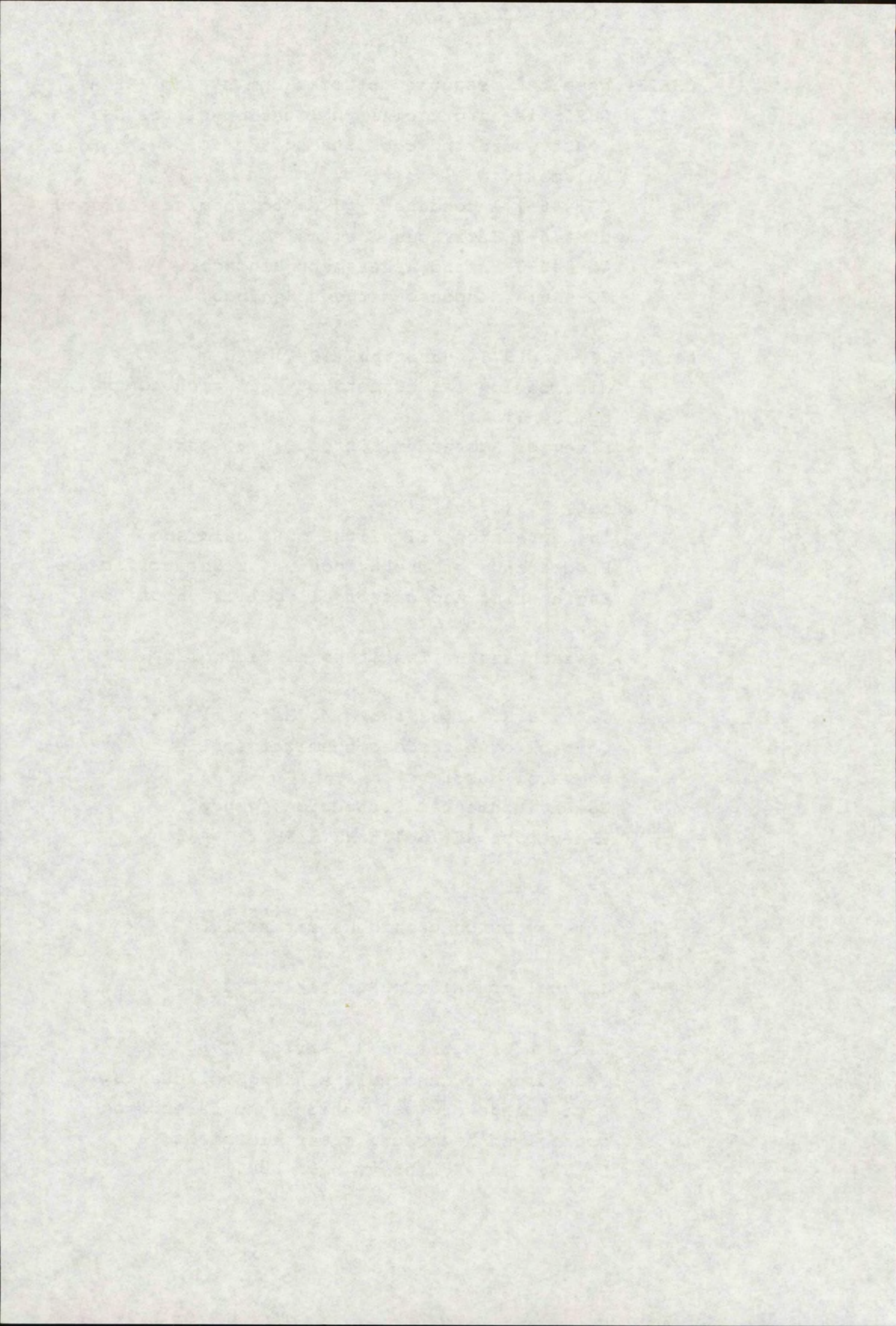
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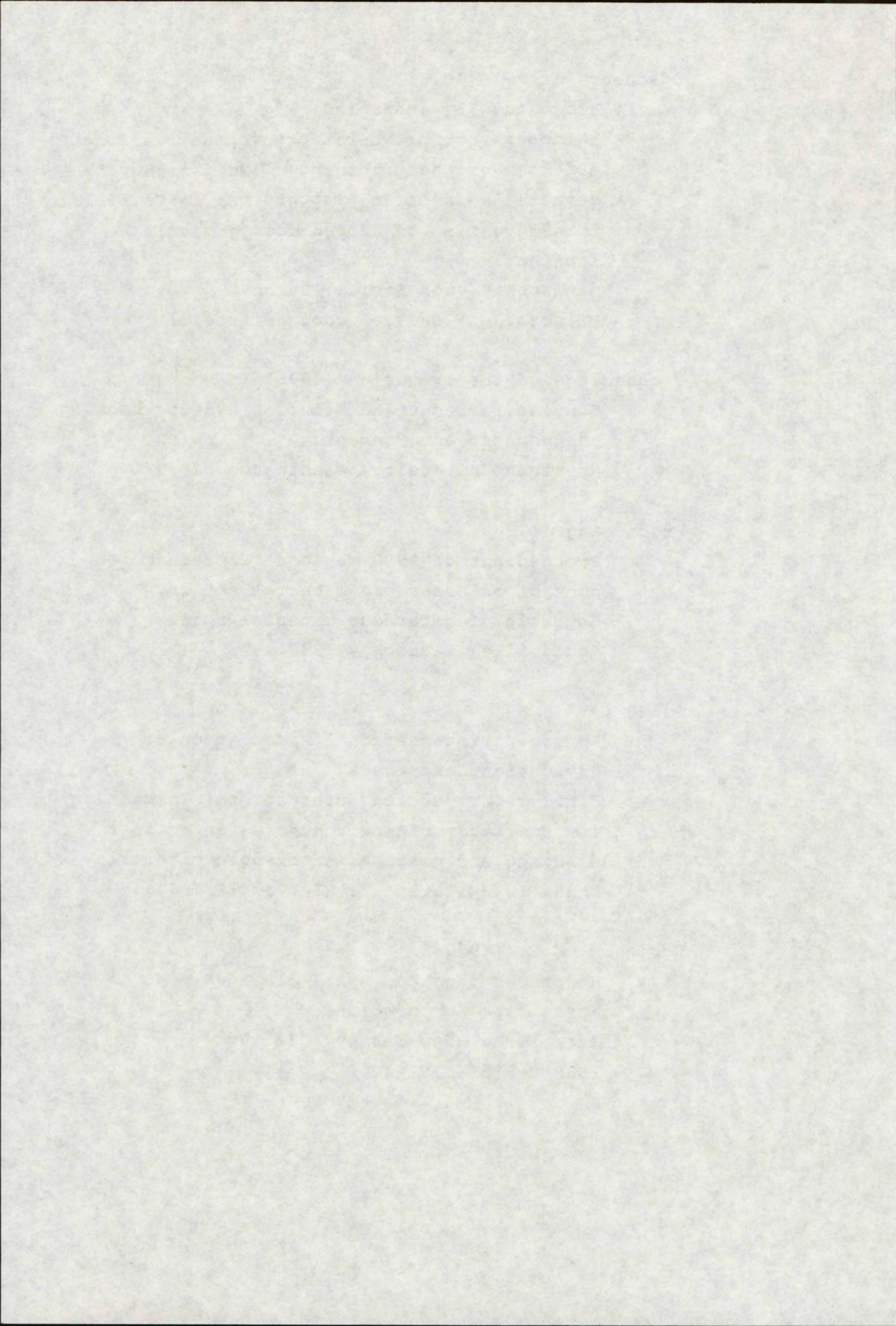
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Appendix I Evaporation

In literature several empirical formulae for calculations on the evaporation of non-boiling liquids can be found. Opschoor (1979) comes after theoretical reflections to a division of the substances in two groups:

- A. substances with a partial vapour pressure
>150 mm Hg, by which the evaporation results in a high mass-flux
- B. substances with a partial vapour pressure
<150 mm Hg, by which the evaporation results in a low mass-flux.

At the same time formulae for both groups are derived. The difference between the results of Group A and B is due to the fact that at high mass-fluxes the mass transfer-coefficient is no longer independent on the mass-fluxes.

Group A: > 150 mm Hg; high mass-flux.

$$Q = 2.10^{-3} \cdot U^{0.78} \cdot r^{-0.11} \cdot \frac{M}{R.T.} \cdot (P_w - P_\infty)$$

Group B: < 150 mm Hg; low mass-flux.

$$Q = \frac{K.M}{R.T.} \cdot (P_w - P_\infty)$$

Q = mass-flux (kg.m⁻²s⁻¹)

U = speed of wind (m.s⁻¹)

r = radius of the liquid pool (m)

M = molecular weight of the substance (kg.kmol⁻¹)

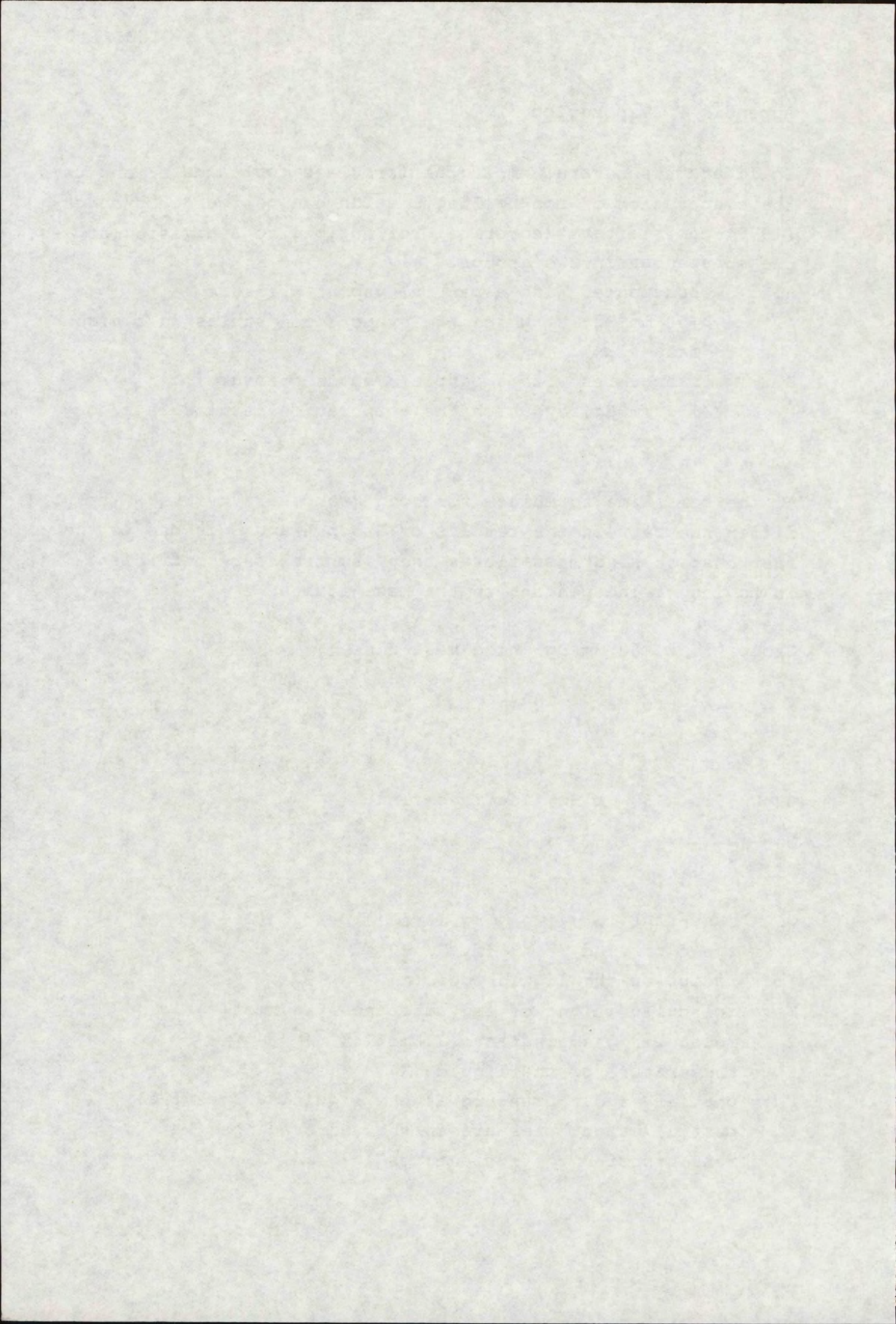
R = molecular gas constant (J.kmol⁻¹K⁻¹)

T = temperature of the liquid (K)

P_w = partial vapour pressure at the liquid surface (Pa)

P_∞ = partial vapour pressure in the surroundings (Pa)

K = mass transfer coefficient (ms⁻¹)



In order to assess the rate of evaporation calculation: made with two substances with a high partial vapour pressure: acetone and hexane and with two substances with a low partial vapour pressure: hexane and acrylacid.

The following assumptions have been made:

- speed of wind: $u = 6 \text{ m/s}$
- radius of the pool: $r = 25 \text{ m}$ — total surface = 200 m^2
- the driving force has to be at most. So the term $(P_w - P_{\infty})$ has to be at most: $P_{\infty} = 0$.

The following constants have been used:

molecular gas constant : $R = 8,3 * 10^3 \text{ J.kmol}^{-1}.\text{K}^{-1}$

mass transfer coefficient: $k = 10^{-3} \text{ m/s}$

1 Pascal = $7,5 * 10^{-3} \text{ mm Hg}$ — $1 \text{ mm Hg} = 133,3 \text{ Pa}$

Results

Group A:

$$Q = 2 \cdot 10^{-3} \cdot u \cdot 0,78 \cdot r^{-0,11} \frac{M}{RT} (P_w - P_{\infty})$$

$$= 2 \cdot 10^{-3} \cdot 60,78 \cdot 250,11 \frac{M}{8,3 \cdot 10^3 \cdot 283} (P_w - 0)$$

$$= 3,2 * 10^{-7} \cdot M \cdot P_w \text{ Hg}$$

P_w is converted to mm Hg : $P_w \text{ Hg}$

Acetone: $M = 58$

$$P_w \text{ Hg} = 180 \text{ mm Hg}$$

$$Q = 3,3 * 10^{-3} \text{ kg/m}^2\text{s}$$

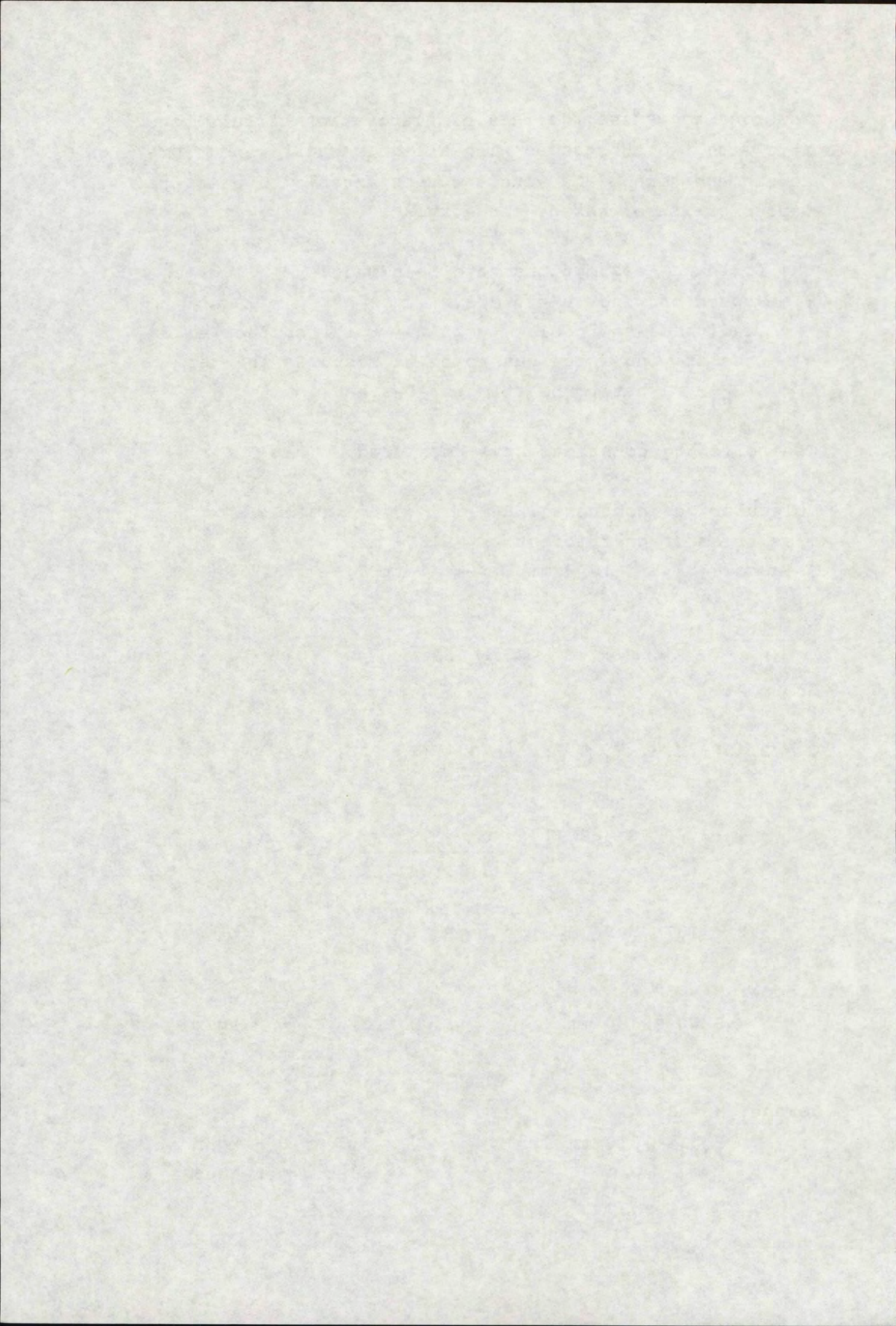
$$= 24 \text{ ton per hour}$$

Hexane: $M = 84$

$$P_w \text{ Hg} = 310 \text{ mm Hg}$$

$$Q = 8,3 * 10^{-3} \text{ kg/m}^2\text{s}$$

$$= 60 \text{ ton per hour}$$



Group B:

$$Q = \frac{K.M}{RT} (P_w - P_\infty)$$

$$= \frac{10^{-3}.M}{8,3 * 10^3.283} (P_w - 0)$$

P_w is converted to mm Hg : $P_w H_g$

$$= 5,7 * 10^{-8}.M.P_w H_g$$

Hexane : $M = 86$

$$P_w H_g = 120 \text{ mm Hg} \quad Q = 5,9 * 10^{-4} \text{ kg/m}^2\text{s}$$
$$= 4.2 \text{ ton per hour}$$

Acrylacid: $M = 72$

$$P_w H_g = 10 \text{ mm Hg} \quad Q = 4,1 * 10^{-5} \text{ kg/m}^2\text{s}$$
$$= 0,3 \text{ ton per hour}$$

