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EVOLUTION OF DRINKING WATER QUALITY IN DISTRIBUTION
Biodegradable Organic Matter and Biological Stability

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T H E F R E N C H E X P E R I E N C E

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August 1992

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EVOLUTION OF DRINKING WATER QUALITY IN DISTRIBUTION

Biodegradable Organic Matter and Biological Stability

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THE FRENCH EXPERIENCE

Dr Catherine Morlay

August 1992

KEYWORDS

- drinking water quality, distribution
- research, France, Universities, Water Companies
- biofilm, residual oxidant, biodegradable organic matter, AOC, BDOC, microbiological analyses
- hydraulic modelling, water quality modelling, treatments, nanofiltration

ABSTRACT

The quality of the drinking water leaving the treatment plants is generally high, according to the current standards, but deteriorates in distribution. Studies carried out in the last decade have demonstrated that the deterioration of the treated waters microbiological characteristics in distribution is due to the formation of a biofilm on the surface of the pipes. The control of the distributed water quality thus necessarily requires the control of the biofilm growth.

A lot of work has been done to endeavour to understand the biofilm formation, to determine its effects on the water quality in distribution and to investigate means of controlling its negative effects. Part of this considerable work has been carried out by French Research Teams, including Universities, as well as private Water Companies. These Research Teams were met in May - June 1992.

The studies carried out on real or pilot distribution systems showed that the residual oxidant (chlorine or chloramines) present in the water leaving the treatment plant at levels used in drinking water production cannot be sufficient to control the biofilm growth.

The Biodegradable Organic Matter (BOM) entering the distribution system was identified as a key parameter of the biofilm growth. This growth can thus be slowed down by the removal of the BOM present in treated water. Several methods have been developed to assess the concentration of BOM in water. The BDOC methods (measuring the Biodegradable Dissolved Organic Carbon) seem to be more relevant than the AOC methods (Assimilable Organic Carbon). Furthermore, the BDOC method developed by Dr Joret and Dr Lévi is the more convenient at the present time. It was used to assess treatment efficiencies to remove the BOM and to observe the evolution of the BOM in distribution.

Mathematical models are being elaborated to explain the removal of the BOM in distribution. These models rely on chemical, biological and physical parameters including the retention time and the velocity of the water in the pipes. A predictive model of coliform occurrences is also being developed.

If the water quality in distribution can be maintained partly by adequate hydraulic conditions and by good maintenance of the mains, efforts have to be made to remove the BOM at the treatment plant. It was found that, in the absence of residual oxidant, a BDOC as low as 0.1 mg C/l can lead to the growth of the biofilm.

The biological stability of the drinking water produced can be improved by the optimisation of the existing classical treatment (mainly coagulation/flocculation) and by the use of new treatment processes such as an ozonation followed by a biological filtration. The lowering of the BOM also reduces the negative effects due to the subsequent use of chlorine in post-disinfection.

The density of micro-organisms in the biofilm is also linked to the amount of micro-organisms entering the distribution system. The nanofiltration, still in development, is a promising process as it is able to remove completely both the organic matter and the micro-organisms of the clarified water. This process is to replace both the ozonation, granular activated carbon filtration and final disinfection.

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INTRODUCTION

Considerable efforts have been made during the last decades to improve drinking water treatments and nowadays the produced drinking water is of a high quality, according to current standards. However, the analyses performed on the distributed drinking water show that the treated water quality, and in particular its microbiological quality, deteriorates in distribution; indeed, high bacterial counts and coliform occurrences are recorded.

There has been increasing concern this last decade over the evolution of the drinking water quality in distribution, in order to understand the deterioration observed so that remedial solutions could be sought.

Studies have demonstrated that the microbiological characteristics deterioration of treated waters in distribution is mainly due to the accumulation of biomass on the surface of the pipes, resulting in the formation of a "biofilm" (Haudidier et al., 1988; Van der Wende et al., 1989; Block et al., 1992). Indeed, any distribution network is an open system receiving micro-organisms coming from the treatment plant or from the outside because of leaks on the mains. Such a system is far from being sterile.

The formation of a biofilm in distribution mains is spontaneous. The development of the biofilm is characterised by three main steps (Bryers and Characklis, 1982; Trulear and Characklis, 1982; Bryers, 1987; Lawrence and Caldwell, 1987):

- the deposit of dead and living micro-organisms and their adsorption on the surface of the pipes,
- the growth (and death) of the living micro-organisms at the expense of the organic matter present in water,
- the erosion of the biomass by the flow of water.

These three steps occur simultaneously in an established biofilm and it is now recognised that the microbiological contamination of the distributed water is the direct consequence of the growth and of the tearing off of the biofilm (Haudidier et al., 1988; Van der Wende et al., 1989; Block et al., 1992). The control of the distributed water quality thus necessarily requires the control of the biofilm development. Moreover, the biofilm corresponds to the starting-point of a food chain leading to the life of small animals in the mains (Lévi, 1990).

Classically, as treated waters are not biologically stable, a disinfectant is introduced at the end of the treatment (generally chlorine or chloramines) from which a durable and constant effect on the water quality in distribution is expected.

The first solution thought of to fight against the microbiological contamination of the distributed water was to increase chlorine dosages applied at the end of the treatment line. This, however, worsens the negative effects subsequent to the use of chlorinated products (appearance of bad tastes and of mutagenic activity due to the formation of organohalogenated compounds). Moreover, this residual concentration of oxidant decreases and disappears in distribution.

The current efforts result from the idea that slowing down the biofilm development is preferable to fighting against its negative consequences. The organic matter entering the distribution system, part of which is biodegradable, has then emerged as the key parameter responsible for the biofilm growth (Lévi and Joret, 1990; Van der Kooij, 1990; Lechevallier et al., 1991; Mathieu et al., 1991). Lowering the concentration of organic matter present in treated water also leads to a decrease in the chlorine demand of the water and consequently to the formation of less chlorination by-products.

The definition of quality objectives for the treated water requires the availability of an analytical tool to assess the concentration of Biodegradable Organic Matter (BOM) in water. This analytical technique must also enable the observation of the drinking water quality evolution in distribution in order to understand and to control the parameters affecting this evolution.

The use of ozone is increasing in all countries; indeed, this oxidant presents many well known advantages in itself and moreover, it is employed as a preventative measure against the negative effects resulting from the use of chlorine. However, it is recognised that ozone increases the biodegradable part of the organic matter present in water (Janssens et al., 1984; Van der Kooij, 1986; Weber and Smith, 1986; Bablon et al., 1987; Joret et al., 1988-1989; De Laat et al., 1991; Ventresque et al., 1991) and its use, unless it is followed by a biological treatment to remove the BOM formed, leads to a greater biological instability of the treated water.

A lot of work has been done in several countries to endeavour to understand the biofilm formation, to determine its effects on the water quality in distribution and to investigate means of controlling its negative effects. Methods were developed to assess the BOM in water. Part of this considerable work has been carried out by French Research Teams, including Universities as well as private Water Companies.

I met these Researchers during a study trip which took place in late May -early June 1992. At that time, the priority was the choice of a method to assess the BOM present in water. Nevertheless, several other topics were approached, such as: the studies carried out on real distribution systems to observe the evolution of the drinking water quality and to identify the main factors controlling this evolution, the water quality modelling, the steps to be taken either at the treatment plant or within the distribution network to reduce the growth of the biofilm.

METHODS USED TO DETERMINE THE BIODEGRADABLE ORGANIC MATTER PRESENT IN WATER

The biodegradable part of the organic matter present in water (raw or treated) may be estimated by a number of different methods. However, some of the methods have been developed quite recently and not much data is as yet available. The method to be used within Yorkshire Water has thus to be chosen from those which have been developed and improved for several years. Only those methods are described in the following.

The main methods used to estimate the Biodegradable Organic Matter (BOM) in water can be grouped into two categories (Huck, 1990):

AOC Methods

These methods are based on the observation of the bacterial growth occurring in the studied water sample. After sterilisation, the sample is inoculated with suspended bacteria which may be pure strains or a natural mixture of indigenous strains (raw river water). The importance of the growth is assessed by the corresponding production of biomass. Depending on the method, the growth indicators are mainly plate counts, adenosine triphosphate (ATP) concentration. During the incubation of the samples, the growth is checked daily and its maximum (ie the maximum number of colony forming units; N_{max} or the maximum concentration of ATP; [ATP] max) is recorded. This maximum value is then expressed in terms of Assimilable Organic Carbon (AOC = carbon metabolised by the bacteria to produce new cells) by means of calibration curves and conversion factors.

BDOC Methods

These methods are based on a direct measurement of the Dissolved Organic Carbon (DOC) which has been chosen as a universal indicator of the organic matter present in water. A decrease in DOC occurs during the incubation of the water sample after a natural bacterial inoculum has been added (suspended bacteria from a raw river water; in this case, the water sample has to be previously sterilised or fixed bacteria attached to sand, sampled in the sand filters of drinking water treatment plants). The fraction of the DOC which disappears during the test is called Biodegradable (BDOC).

The main methods now used to determine the amount of BOM in water are listed in the table shown on the next page.

With these methods the results are generally obtained after a few days (5 to 10 days) except for the Servais - Billen method where four weeks of incubation are required.

M A I N M E T H O D S U S E D F O R A O C A N D B D O C D E T E R M I N A T I O N S

TYPE OF MEASUREMENT	METHOD DEVELOPED BY	COUNTRY	INOCULUM		PARAMETER
AOC	Van der Kooij et al., 1982	Netherlands	Pure strains (1 or 2)	Suspended	Plate counts
AOC	Kemmy et al., 1989	USA	Pure strains (4 in a mixture)	Suspended	Plate counts
AOC	Jago - Stanfield, 1987	UK	Natural	Suspended	[ATP]
AOC *	Werner, 1985	Germany	Natural	Suspended	Turbidity
BDOC	Servais - Billen, 1987	Belgium	Natural	Suspended	DOC
BDOC	Joret - Lévi, 1986	France	Natural	Fixed (Sand)	DOC

* This method does not provide a result expressed as a carbon concentration. It is regarded as an AOC method as it is based on the observation of a bacterial growth.

STUDIES CARRIED OUT IN FRANCE ON THE EVOLUTION OF DRINKING WATER QUALITY IN DISTRIBUTION

The following presents the main conclusions which have been drawn up to the present time and the studies going on in France. The subjects approached with the researchers were not only relative to the choice of a method to determine the Biodegradable Organic Matter in water but were also relative to other topics, such as the means to control the biofilm formation, the studies carried out in distribution systems and the water quality modelling.

1. CIRSEE (Centre of International Research for Water and Environment) Research Centre of Lyonnaise des Eaux - Dumez - Le Pecq

Two main questions have been raised during the conversation with Dr Laurent Ki  n  , Nadine Dumoutier and Philippe Piriou: firstly, the assessment of the Biodegradable Organic Matter (BOM) and, secondly, the water quality modelling.

1.1 Assessment of the BOM

The method developed by Werner has been chosen to estimate the BOM in water. The production of biomass is assessed by the continuous measurement of the turbidity during the incubation of the studied water sample. This method does not provide results expressed in terms of a carbon concentration but allows the rate of growth (μ) and the cellular conversion yield (Y) to be calculated. These parameters give an idea, respectively, of the degree of biodegradability of the organic matter and of the fraction of this organic matter which is available for the bacterial growth.

The results are obtained quite quickly (three to five days), the turbidity measurement is automatised and the data is handled by a computer. However, a turbidimetre is required for each sample analysed. This makes the method costly to perform and prevents the analysis of a large number of samples. Moreover, the interpretation of the results obtained (μ and Y) is not obvious and no conclusion has as yet been drawn on the evolution of the water quality in distribution.

Otherwise, the ATP method has been used to assess the BOM present in water but no valuable results have been found.

1.2 Water Quality Modelling

Lyonnaise des Eaux - Dumez has developed its own hydraulic modelling which allows the calculation of the flow rate and of the residual chlorine concentration at any point of the distribution system over a period of 24 hours (maps can also be drawn). This model may also be used to simulate the fate of a pollutant accidentally introduced into the distribution system.

2. Laboratoire de Chimie de l'Eau et des Nuisances (Water Chemistry Laboratory) - University of Poitiers

Dr Nicole Merlet has assessed different methods for the measurement of the BOM. These are the methods of Joret - Lévi, Servais - Billen and Jago - Stanfield. For the last method, the detection limit in the analysis of ATP was found to be too high to enable the study of the water quality evolution of treated waters. The method developed by Servais - Billen was thought to be far less time-consuming than the method of Joret - Lévi, as only two DOC determinations are needed (one on the first day of incubation and one on the 28th day). However, the delay required to obtain the BDOC results remains the major drawback of the method.

The laboratory also took part in the international round-robin trials organised by Professor J C Block. At this time, experiments are carried out with the method of Joret - Lévi, in parallel with the determination of amino-acid concentrations in water. The amino-acids have an important chlorine demand and it is known that part of the chlorine demand of a water is due to biodegradable organic molecules. This study has been undertaken in collaboration with Anjou Recherche (Compagnie Générale des Eaux Research Centre).

Dr N Merlet also spent one year in the Polytechnic School of Montreal (Quebec) where she studied the efficiency of Granular Activated Carbon (GAC) filters to remove the BOM from treated waters. She also characterised the nature of the organic molecules likely to be biodegraded and assessed their effect on the chlorine demand of the ozonated and GAC filtrated water.

As good relationships have been established between the two laboratories, I had the opportunity to meet Dr Raymond Desjardins in Poitiers (see paragraph 6.2).

3. NAN.C.I.E. - International Water Research Centre - Nancy

A number of different organisations are involved in the field of water in Nancy. In 1985, 18 public or private research laboratories grouped to form the NAN.C.I.E., the General Director of which is Professor Jean-Claude Block.

NAN.C.I.E. is thus able to provide a multi-disciplinary approach and to co-ordinate common actions within numerous partners (research laboratories, departments from territorial organisations, firms in the water industry and transfer bodies) in many fields of research (water resources, treatment of drinking and wastewater, drinking water distribution, wastewater collection and sewage networks, sludge treatment, recreational waters and chemical products in water treatment).

The Water Centre brings together numerous facilities for research, analysis (the analytical platform is recognised as being one of the major ones in Europe) and experimentation (technical halls and pilot facilities for treatment plants and networks).

With its pool of experts in varying disciplines, NAN.C.I.E. enjoys national recognition (both from water companies and official agencies such as the Environment, Research and Health Ministries) as well as international recognition (for example, by the US Environmental Protection Agency). It is also being increasingly called upon to act on behalf of French and foreign territorial organisations (35 countries). NAN.C.I.E. collaborates with the World Health Organisation (WHO). European laboratory networks are being organised such as that concerned with "measuring levels of biodegradable organic matter in water", which groups together 16 laboratories in eight countries (France, Belgium, Spain, Germany, Sweden, the USA, Canada and the UK). The United Nations is preparing to set up a Projects Department in Nancy for the Environment and Health. It will have to develop a partnership between the 32 countries of the European Region of the WHO and the international capital investors.

Among the applied research programmes currently in progress, one is relative to drinking water with the study of:

- the accumulation of biofilm in drinking water distribution systems
- the impact of drinking water treatment lines on the biofilm in distribution networks.

Dr Vincent Gauthier, working in NAN.C.I.E., organised meetings with researchers from two main laboratories of NAN.C.I.E.: the Institute of Hydrological Research and the Health - Environment Laboratory. I also had the opportunity to see the drinking water treatment and distribution system pilot plants located in the NAN.C.I.E. premises.

3.1 IRH - Hydrological Research Institute

IRH is an applied study and research centre (private status) having acquired experience in the fields of water (drinking or wastewater), sludge and waste (urban or industrial) over more than fifty years. Its services are not only concerned with the scale up of research work but also include the definition and construction of any water treatment, activities of counsel and construction management and technical assistance.

IRH is an official analyst by agreement of the French Public Health Officer of public distribution waters and a regular contributor to French Government authorities. It has privileged connections with the university world and co-operates with international organisations.

Two of its main axes of research are:

- the study of water/materials interactions (scaling, electrochemical and bacterial corrosion, biological deterioration of materials
- the development of the instrumentation applied to the water quality measurement in treatment plants and distribution networks.

Among its consultancy activities, it carries out diagnostic studies of networks and hydraulic conception and management of water networks, including modelling.

The IRH is also involved in the study carried out by NAN.C.I.E. on the biofilm growth in drinking water distribution systems.

3.1.1 Contribution of IRH to the Biofilm Study

The IRH performs both chemical and microbiological analyses. The chemical analyses include the identification and dosage of chlorination by-products. Concerning the microbiological analyses, Dr Jean-Luc Paquin gave a full explanation of the bacterial numeration by epifluorescence microscopy (which allows counting both dead and living bacteria present in water or in the biofilm), eventually using image analysis.

3.1.2 Drinking Water Quality Modelling

The pipes of drinking water distribution networks can be considered as physico-chemical, chemical and biological reactors, modifying, in time, the quality of the distributed water. All the main phenomena involved are linked with water retention time inside the network and depending on the kinetic laws governing the phenomena.

The modelling of drinking water quality must include:

- hydraulic modelling to estimate not only the mean value of the age but the age distribution of the water at each water point of use or network node,
- modelling of the main phenomena involved, including the purely physical aspects of the mixing of waters coming from different sources and its consequences for non-reactive chemical species.

a) Hydraulic Modelling

IRH developed its own hydraulic modelling (AREMAN: Analysis of Meshed Networks by the Nodal Method). This package allows both the hydraulic analysis and the dynamic modelling/simulation of the network to be carried out. A demonstration showed how convivial the use of this package is.

The AREMAN software module gives, at any time during the water consumption cycle (daily or weekly), the pressure at any node, the flow rate, the velocity and the direction of the water inside any pipe of a meshed network. It also calculates the age of the water at each node.

b) Water Quality, Due to non-Reactive Species, Modelling

The simplest case for water quality modelling is the one when a conservative (non reactant) substance is introduced anywhere in the network. The aim of the model is to describe its movement over a period of time and calculate its concentration in all areas.

Interesting application cases are:

- the simulation of tracer experiments
- water quality modelling in networks fed by several different quality sources, for instance to study the concentration of undesirable species (nitrates).

The software module maps out the migration of the selected species during the time following its introduction, at every node (particularly into reservoirs) during a daily or weekly cycle.

It also determines the concentration of the non reactant species in time taking into account the characteristics of the substance injection and of the network function during the studied period.

c) Water Quality, due to Single Chemical or Biological Reactions, Modelling

The case is more complex than the preceding one due to the existence of one or more reactions which consume or produce chemical species.

In the same manner as before, a software module maps out the migration of the reactive species through the network and determines the concentration of the reactive species with time, taking into account the kinetics of the involved reaction and the operational parameters of the network during the studied period.

At the present time, the software module uses simple kinetic equations of the form $v=kC^n$ where the reaction order is a whole or a fractional number between 1 and 2.5. The first studied application is the modelling of free chlorine disappearance in the networks.

Other interesting applications to consider are:

- specific chemical reactions between free chlorine and water constituents (ammonia, organic matter),
- dissolved organic matter biodegradation in liquid phase,
- bacterial growth in liquid phase.

However, according to representatives from the IRH, the described works must be considered only as a first approach to the water quality modelling problem in distribution networks. Further progress must come from:

- taking into account more complex reactions (for instance microbial growth) and eventually heterogeneous reactions involving the inner surface of the pipes,
- adjustment of the models by systematic measurements and monitoring operations on real large-size networks.

3.2 Laboratoire Santé - Environnement (Health - Environment Laboratory) - University of Nancy

The visit to the University of Nancy included the oral presentation of the PhD thesis of Mrs Laurence Mathieu and a further discussion with L Mathieu and Professor Jean-Claude Block. This presentation was the opportunity to have a summary on recent work carried out in the laboratory of Professor J C Block on water quality in distribution. It was also the opportunity to meet Dr Pierre Servais from the University of Brussels, Belgium and Dr Michelle Prévost from the Polytechnic School of Montreal, Quebec (see paragraph 6).

3.2.1 Presentation of the PhD Thesis of Dr Laurence Mathieu

Dr Laurence Mathieu presented the four year research work she carried out in the laboratory of Professor J C Block. Her thesis is entitled:

"Biodegradable organic matter and biological stability of drinking water in distribution".

The experimental work consists of three parts:

- a) measurement of the Biodegradable Dissolved Organic Carbon with indigenous bacterial inocula,
- b) fate of the Biodegradable Dissolved Organic Matter in a real distribution system,

c) pilot study of the parameters controlling the bacterial growth in mains.

a) **Measurement of the Biodegradable Dissolved Organic Carbon with Indigenous Bacterial Inocula**

Indigenous bacterial inocula offer key advantages:

- mixed indigenous bacterial populations are more efficient in utilising a mixture of natural organic molecules than are pure bacterial strains,
- mixed indigenous bacterial populations can be easily sampled in the environment (river water) or in water treatment plants (bacteria attached to sand) without specific preparation, storage or transport problems
- no pretreatment of water samples, such as sterilising, filtration or pasteurisation, is required.

However, their validity in the measurement of BDOC, that is to say their possible use as a standard reagent, had to be demonstrated. A collaborative study was undertaken which involved seven European laboratories (including Professor Pierre Servais from the University of Brussels, Belgium and Professor Pieter Werner from the University of Karlsruhe, Germany).

This round-robin test was carried out using the same river water sampled at various treatment stages (raw water, ozonated treated water before GAC filtration, post-chlorinated finished water). Two types of indigenous inocula were used: - suspended bacteria (Servais - Billen method) from five different surface waters and fixed bacteria attached to sand (Joret - Lévi method) from sand filters of five different drinking water treatment plants.

A statistical analysis of the data showed that, for the two methods, the greatest source of variance of the BDOC results (60% to 70%) was associated with the laboratories (ie experimental conditions and operation) whereas the variations introduced by the inoculum origin were far lower (10% to 30%). This result is of great importance; indeed, it means that the geographical origin of the inocula only slightly affects the BDOC measurement and that consequently environmental indigenous inocula (ie mixed population of suspended or attached bacteria sampled from the field) may be used for the BDOC determination without introducing excessive variability. This implies that the use of environmental inocula could no longer be regarded as an obstacle to the standardisation of the methods under study.

Furthermore, this settles problems related to the preparation and distribution (storage, transport, contamination) of a standardised inoculum of pure bacterial strains and the need for pretreatment of the samples (filter sterilisation or pasteurisation).

The results obtained in this study also showed that:

- the variability of the BDOC values were higher when suspended bacteria were used; furthermore, in this case, the dispersion of the results was dependent on the amount of BDOC initially present in the sample of water,
- the results of BDOC determinations were obtained after 3 to 9 days of incubation for the samples inoculated with a fixed biomass whereas 17 to 21 days were needed in the case of an inoculation with suspended bacteria,
- the BDOC values obtained with a fixed biomass were greater (1.2 to 1.5 times) than that observed with a suspended biomass in similar experimental conditions; even after 21 days of incubation, suspended bacteria proved to be less effective in the biodegradation of the organic matter.

b) **Fate of the Biodegradable Dissolved Organic Matter in a Real Distribution System**

In the distribution system under study, the river treated water was provided by only one drinking water treatment plant and no secondary chlorination was performed in distribution. Two sampling campaigns were planned - one in summer (July - August 1989) and one in winter (February 1990), allowing the study of treated waters of different quality and of different temperatures in the distribution system. In each case, more than a hundred samples were collected at consumer taps and at the end of the treatment line at the water treatment plant.

Twelve parameters were measured on each sample, including classical analysis (pH, free and combined chlorine concentration, temperature, conductivity) and more specific analyses allowing the characterisation of the distributed water in terms of organic matter (fluorescence, UV absorbance, DOC, BDOC) and of bacterial density (plate counts after 3 and 15 days of incubation, counts using epifluorescence microscopy). The BDOC determinations were performed using the method of Joret - Lévi (fixed bacteria).

This data allowed a characterisation of the treated water entering the distribution system and the study of the evolution of the water quality in distribution. It was also used in order to assess the possible prediction of the bacterial density and of the fate of the biodegradable organic matter in distribution.

Characterisation of the Treated Water

The results showed a clear influence of the season (average temperatures of 8°C and 18°C) on the water quality at the end of the treatment line:

- DOC and BDOC concentrations were higher in summer (winter values: 2.0 and 0.3 mgC/l respectively; summer values: 2.5 and 0.8 mgC/l respectively),
- the BDOC accounted for 16% of the DOC in winter and for 32% of the DOC in summer,
- the numbers of CFU (72 hours incubation time) and of total cells (dead and living bacteria counted by epifluorescence microscopy) present in water was higher in summer (147 and 3 times respectively).

However, the average concentrations of free chlorine (0.69 and 0.68 mg Cl₂/l) and the pH (7.9 and 7.8) did not vary significantly.

Evolution of the Water Quality in Distribution

All the studied parameters evolved between the end of the treatment and the distribution system considered as a whole. Generally, these parameters evolved in the same direction in summer as in winter but the amplitudes of these evolutions varied.

The greatest variations (at least 5% to 10% between the end of the treatment and the distribution system considered as a whole) were observed with the temperature, the residual oxidant concentration (free or combined chlorine), the amount of organic matter (DOC) and the density of bacteria in water.

The temperature always increased in distribution. For the other three parameters, a statistical analysis of the data showed that, in summer and in winter:

- 50% to 60% of the studied distribution system contained water without free chlorine residual and 30% contained water with a residual lower than 0.1 mg Cl₂/l,
- the density of bacteria (CFU - 72 hours or epifluorescence microscopy counts) increased to more than 80% in distribution; the European standard of 100 CFU/ml was exceeded in 4% of the distribution system in winter and in 30% of the distribution system in summer with values reaching 150 - 200 CFU/ml (and 3.10⁶ cells/ml),

- 20% of the distribution system had a DOC higher than that measured on the water at the end of the treatment (average values of 2.4 and 1.8 mg C/l in summer and in winter respectively); however, these values were obtained on samples of various geographical origins, not characteristic of a specific area.

On the remaining 80% of the distribution system, around 60% in summer and 30% in winter had a lower DOC than that measured on the treated water sampled at the end of the treatment. These results suggest that, in terms of organic matter, the distributed water is more stable in winter than in summer.

The statistical analysis of the data (polynomial regression by the Stepwise method) allowed the identification of the variables able to explain the evolution of the BODC in distribution. These variables are, in a decreasing order of importance:

in summer

DOC, conductivity, number of bacterial cells (epifluorescence counts) and temperature

in winter

DOC, UV absorbance, number of bacterial cells (epifluorescence counts), combined chlorine concentration and pH.

In each case, the DOC values provide the greatest contribution to the prediction of the fate of the biodegradable organic matter in distribution. A simple linear relation between the BDOC and the DOC concentrations showed that the DOC alone could explain 89% of the variations in the BDOC in summer and 65% of the variations in winter. Furthermore, this linear relation between DOC and BDOC allowed the estimation of the non-biodegradable part of the DOC which is called "Refractory" (RDOC). The average values of 1.6 and 1.5 mgC/l found in summer and in winter respectively are similar to those measured on a number of treated surface waters.

Concerning the possible prediction of the bacterial density in the distribution system, no reliable correlations were found between the level of organic matter in water (DOC and BDOC) and the results of plate counts or epifluorescence microscopy counts. However, at least a partial overlap was observed between the areas with the highest bacterial densities and the areas of the distribution system with the greatest residence times of the distributed water.

c) **Pilot Study of the Parameters Controlling the Bacterial Growth in Mains**

The study of a real distribution system proved to be difficult as a number of different parameters varied at the same time. In order to understand the evolution of the water quality in distribution, a pilot study was undertaken. For this purpose, an experimental distribution system of industrial size was built by the International Water Centre in Nancy. This device allowed the control of the characteristics of the studied distribution system.

The objectives of the study were:

- to observe the evolution of the water quality in distribution (residual oxidant concentration; organic matter; bacterial density),
- to compare the effect of chlorine and chloramines used in post-disinfection on the biological stability of the distributed water,
- to try to explain the bacterial densities measured in the distribution system by looking for quantitative relations between those and either the residual oxidant concentration or the amount of biodegradable organic matter present in the water.

The experimental distribution system comprises three identical loops (31m length x 0.1m internal diameter) in series. The pipes are made of cast iron inwardly overlaid with cement.

The pilot was fed with a river treated water (pre-chlorination, clarification, post-disinfection) at a flow rate of 10l/h so that the residence time of the water in each loop was 24 hours. In each loop, the pressure was of 1 to 1.3 bar, the velocity of the water was 1m/s, the temperature was around 20°C and 21 probes allowed direct measurements of the biofilm to be performed.

The BDOC determinations were carried out both with the methods of Joret - Lévi and of Servais - Billen. Bacterial densities were measured both in the water and in the biofilm using plate counts (3 and 15 days of incubation) and epifluorescence microscopy counts (dead and living bacteria).

The results obtained during this two year study showed:

in the presence of residual oxidant ($\text{Cl}_2 = 0.36\text{mg/l}$;
 $\text{NH}_2 \text{Cl} = 1.06 \text{ mg/l}$):

- there is no or little biodegradation of the organic matter and there is no or little bacterial growth. Thus, the presence of micro-organisms on the pipes is mainly due to the deposit of cells brought by the treated water; a linear relation between the logarithm of the number of cells in the biofilm and the logarithm of the number of cells entering the distribution system was found. Furthermore, the statistical analysis of the data showed that the absence of cells in the water would lead to a decrease of 10 to 1000 times the number of cells in the biofilm (initial concentration = 10^4 to 10^6 cells/cm²).
- according to the statistical analysis of the data, to comply with the European standard of 100 CFU/ml, a residual of chlorine of 1.2 mg Cl_2/l or a residual of monochloramine of 0.5 mg Cl_2/l should be maintained in the distribution system. To avoid the formation of a biofilm, these values should be of 1.8 and 3.0 mg Cl_2/l respectively. These results show that chlorine is twice as efficient as chloramines in killing planktonic bacteria and that chlorine is three times more efficient in avoiding the formation of biofilm on the pipes.

in the absence of residual oxidant

- the concentration of organic matter is the primordial parameter responsible for the accumulation of bacteria on the surface of the pipes. The consumption of the organic matter leads to an increase of the bacterial density, mainly in the biofilm,
- a concentration of BDOC of 0.1 mg C/l still leads to a bacterial growth. The model failed to provide a threshold limit of BDOC preventing this growth. Thus, it was suggested that any biodegradable organic matter entering the distribution system would lead to a bacterial growth in the biofilm.

3.2.2 Conversation with Professor J C Block and Dr L Mathieu

The main subject of this conversation was the choice of a method to assess the Biodegradable Organic Matter (BOM) present in water. Professor Block first used AOC methods (Assimilable Organic Carbon). At this time, it was thought that only the use of pure bacterial strains could allow the standardisation of a method to assess the BOM. However, following the round-robin trial organised by Professor Block, it was decided to use only indigenous inocula which have key advantages compared to inocula of pure bacterial strains (see paragraph 3.2.1 - a). Furthermore, these last ones have proved to be not so easy to standardise.

The ATP method (method of Jago - Stanfield) was one of the different AOC methods assessed in the laboratory of Professor Block. However, it is no longer used as it was found to be a poor tool to estimate reliably the BOM.

4. COMPAGNIE GENERALE DES EAUX - PARIS

Compagnie Générale des Eaux is carrying out a study in order to assess the effects of a nanofiltration stage on the formation of the biofilm in a real distribution system (suburb of Paris). The nanofiltration stage, set at the end of the drinking water treatment line, will replace the following existing treatment steps: ozonation, GAC filtration, ozonation and final chlorination. Thus, a considerable (almost total) decrease of the DOC (and consequently of the BDOC) and a complete removal of the micro-organisms are expected from the nanofiltration treatment.

This study includes the characterisation of the water quality and of the biofilm formation before and after the use of nanofiltration in the treatment line. In this purpose, the following parameters are measured in the water:

- temperature
- residual chlorine concentration
- DOC and BDOC (method of Joret - Lévi)
- sanitary indicators (including coliforms)
- bacterial densities (plate counts and numerations using epifluorescence microscopy)
- bacterial growth dynamics.

The bacterial growth dynamics are assessed by the method developed by Professor Gilles Billen (University of Brussels, Belgium). This method allows the calculation of the growth kinetic of the biofilm on the surface of the pipes. To carry out this determination, measure chambers have been built on several parts of the distribution system. Each chamber contains a special device fitted on the studied pipe from which the biofilm has to be sampled. The bacterial density in the biofilm is then determined by plate counts and by epifluorescence microscopy counts.

Before starting the analyses on nanofiltrated distributed water, the distribution system will be cleaned. A public opinion poll has been carried out before changing the water treatment line.

It should be emphasised that such a study, involving the building of measure chambers in the distribution system, is carried out only for research purposes.

Finally, a model will be built to try to predict the areas of the distribution system where the biofilm could preferentially form. Such a model will rely on the physical, chemical and biological data collected on the distribution system and the existing hydraulic modelling.

5. ANJOU RECHERCHE - RESEARCH CENTRE OF COMPAGNIE GENERALE DES EAUX - MAISONS LAFFITTE

Different subjects were approached during the conversation with Dr Jean-Claude Joret. The main topics were:

- the comparison of the different existing methods for the Biodegradable Organic Matter (BOM) assessment in water,
- the means to prevent biofilm formation,
- the study carried out on a real distribution system which was the design basis of a coliform occurrences predictive model.

5.1 Comparison of the Different Methods for the Assessment of the BOM in Water

Dr J C Joret and Christian Volk (PhD student) assessed the relevance of both AOC and BODC methods to determine the BOM in water. The ATP method (method of Jago - Stanfield) was one of those assessed.

However it is no longer used as it proved unable to detect changes in water quality through the different treatment stages as distinctly as the BODC method they employ. Furthermore, the detection limit of the method was found to be too high to allow the fate of the BOM in distribution to be studied (as the concentration of ATP in water is too low at the end of the treatment line).

In 1986, Dr Joret and Dr Lévi developed a new BODC method which uses an indigenous inoculum of fixed bacteria (attached to sand taken from sand filters of a drinking water treatment plant). The objective of developing this new method was to shorten the response time needed in the BDOC method previously set up by Servais - Billen and using an inoculum of suspended bacteria.

This method was submitted to international round-robin trials organised by Professor Block and it proved to be a good tool to assess the BOM in water. It has now reached a level of reliability which allows its standardisation. Indeed, this method will be pre-standardised in France by the end of the year and a number of laboratories will thus be able to use it in similar experimental conditions.

Also, Dr Joret has worked in collaboration with Dr L A Kaplan (from the United States Environmental Protection Agency) and the BDOC method using fixed bacteria may be included in the 18th edition of the American Standard Methods.

Finally, concerning the methods being recently developed, Anjou Recherche is involved in a collaborative study in order to assess a dynamic measurement of BODC tried out by F Ribas, J Frias (Sociedad General de Aguas de Barcelona, Barcelona, Spain) and F Lucena (University of Barcelona, Spain). This method would provide the BDOC results in a few hours, allowing a possible action on the treatment line efficiency. The laboratory of Dr L A Kaplan (Stroud Water Research Center of the Academy of Natural Sciences of Philadelphia, USA) is the third to be involved in this study.

5.2 Study Carried out on a Real Distribution System

A study has been carried out in order to assess the evolution of the water quality in distribution. Five sampling points were chosen on part of a distribution system in Paris suburb, considering their distance to the drinking water treatment plant (around 4, 7, 9 and 17 kilometres) and the approximate residence time of the water in the mains (presence of service reservoirs). The water quality was also recorded at the end of the treatment line. This treatment line (the same as that used by CGE for its study) includes clarification, GAC filtration, ozonation and chlorine post-disinfection steps.

During one year, the following parameters were measured at the six sampling points:

- physico-chemical parameters: temperature, turbidity, residual chlorine concentration, DOC and BDOC (method of Joret - Lévi),
- bacteriological parameters: sanitary indicators, bacteria growing at 20°C and 37°C, plate counts on R2A culture medium (3 and 11 days of incubation) and total bacteria counts using epifluorescence microscopy (dead and living bacteria).

The results obtained at the drinking water treatment plant showed that:

- the higher the BDOC concentration in raw water, the higher the BDOC concentration in finished treated water (mainly in winter and spring),
- depending on the period of the year considered, the BDOC is around 1.5 to 2.0 mgC/l for the raw water and 0.5 to 1.0 mgC/l for the finished water,
- the efficiency of the treatment line in removing the BDOC of the raw water is higher in summer.

The results obtained on the distribution system showed that:

- the bacterial growth is associated with
 - an increase of the temperature and of the distance from the treatment plant, which corresponds to an increase of the residence time of water in the mains,
 - a decrease of the residual chlorine concentration and of the BODC present in water, which also corresponds to an increase of the residence time of water in the mains,
- a total consumption of the BDOC of the finished water (measured at the end of the treatment line) can occur during the distribution; this consumption is favoured by an increase in the water temperature and in the residence time in the distribution system,
- some coliform occurrences were observed, mainly in summer (from July to October); this pattern is explained by a higher growth rate of the biofilm with higher temperatures, leading to a more frequent tearing off of the biofilm and to a subsequent release of the coliforms living in (growing in or trapped by) the biofilm.

From the statistical analysis of the data (Principal Component Analysis and Multiple Linear Regressions) obtained over one year, three models were set up, allowing the prediction of:

- heterotrophic plate counts from the residual chlorine concentration and temperature (coefficient of prediction around 80%),
- BDOC consumption in distribution from the BDOC level at the end of the treatment and temperature (coefficient of prediction around 55%),
- coliform occurrences from the amount of BDOC consumed in distribution, epifluorescence microscopy counts and temperature (coefficient of prediction around 30%).

At this time, the last model can only predict the peaks of coliform occurrences but cannot predict the amplitude of these peaks. This explains the low coefficient of prediction found in this case (it should be noted that the residual chlorine concentration has not been identified as one of the main parameters affecting coliform occurrences). However, according to Dr Joret, the model allows the expectation of a coliform occurrence 15 days in advance (allowing preventive action to be taken) but it still has to be improved.

The general conclusion of this study is that there are two means of controlling the water quality in distribution which are: the increase of the residual chlorine concentration in the distributed water and the decrease of the BDOC concentration of the finished treated water. If the first of these means is limited (negative effects due to high chlorine dosages, decrease and even absence of residual chlorine in some parts of the distribution system), the second one is now well recognised as the way for further work.

The results of this study have not been published yet but were nevertheless kindly presented both by Dr Joret and Christian Volk.

6. OTHER RESEARCH TEAMS WORKING ON THE EVALUATION OF WATER QUALITY IN DISTRIBUTION

This stay in France provided the opportunity to meet Dr Pierre Servais from the University of Brussels, Dr Michelle Prévost and Dr Raymond Desjardins from the Polytechnic School of Montreal.

6.1 University of Brussels

Dr Pierre Servais and Dr Gilles Billen have developed a BDOC method using indigenous inocula of suspended bacteria. This method has been submitted to the international round-robin trials organised by Professor Block and it is one of the two methods (with the method of Joret - Lévi) which will be pre-standardised in France by the end of the year.

Dr Servais and Dr Billen have worked closely with the Health - Environment Laboratory in Nancy and with Compagnie Générale des Eaux (CGE) on the biofilm understanding in relation to the evolution of water quality in distribution. The study carried out with Y Lévi, G Randon and P Laurent (from CGE) on one of the Paris suburb distribution systems has led to the setting up of a model to predict the fate of the biodegradable organic matter and the bacterial growth in distribution.

6.2 Polytechnic School of Montreal

Dr Michelle Prévost and Dr Raymond Desjardins, from the Polytechnic School of Montreal (Department of Civil Engineering and Environment), have worked closely for several years with the City of Laval to improve the quality of the treated water produced by the city drinking water treatment plants. In particular, they studied the efficiency of ozonation followed by GAC filtration on the removal of biodegradable organic matter.

The City of Laval subsequently considered where to expend more effort to improve the water quality of the distributed water (ie increase the degree of treatment of the water and/or improve the distribution conditions of the treated water). As this problem also concerns many other drinking water suppliers, an important study has been undertaken to assess both the "water effect" (which is linked to its degree of treatment) and the "distribution system effect" on the evolution of the water quality in distribution.

The main objectives of this three year study, partly funded by the Canadian Scientific Research Centre, are as follows:

- to develop analytical techniques to assess the regrowth potential of the water,
- to identify the water characteristics and the reasons for regrowth in the mains (determination of the "water effect" versus the "distribution system effect"),
- to develop the data processing support to integrate the qualitative aspect to the quantitative aspect of the water distribution modelling,

- to assess the effect of steps taken within the distribution system on the evolution of the water quality,
- to identify technical solutions, relative both to the treatment and to the network maintenance, able to insure the preservation of the water quality in distribution (including the corrosion problem).

To achieve this study, the Polytechnic School of Montreal employ not only its experience in the field of water analysis (AOC - BDOC, microbiological analyses including coliform regrowth potential, bacterial activity, epifluorescence microscopy) but also its close collaboration with the City of Laval (for the hydraulic modelling of the distribution system which has already been running for 3 years). Thus, a model has already been set up to predict the fate of the biodegradable organic matter in distribution.

Finally, a working party has been formed at the Polytechnic School of Montreal to study:

- the effect of different oxidants
- the effect of biological treatments
- the regrowth in mains
- the new treatment processes (including membranes)

on the evolution of water quality in distribution.

1. Choice of a method to evaluate the Biodegradable Organic Matter present in water

The biodegradation of the organic matter is responsible for the deterioration of the quality, and especially of the microbiological quality, of the distributed water. Several methods have been developed to assess the amount of Biodegradable Organic Matter (BOM) present in treated water. They can be grouped in two categories: AOC methods and BDOC methods.

At the present time, no method has given rise to an international consensus. However, in the light of the existing literature and of the information obtained during the stay in France, the choice of a BDOC method seems to be preferable for several reasons.

Firstly, AOC methods, due to the principle on which they are based, cannot but underestimate the BOM present in the water for two main reasons:

- these methods take into account only the part of the substrate that can be easily used to produce new cells (AOC is also called easily assimilable organic carbon), ignoring the part of the BOM metabolised by the micro-organisms for their survival or considering it constant in all the experiments,
- the calculation of the AOC value is based only on the maximum of growth (Nmax or [ATP]max) observed during the test, ignoring the part of the substrate that has been metabolised before and after this maximum of growth has been reached or considering it constant in all the experiments.

Furthermore, the calculation of the AOC value from the maximum of growth observed during the test (and expressed as a number of cells or a concentration of ATP) requires the use of calibration curves and of conversion factors, the relevance and the accuracy of which have been proved to be arguable. Thus AOC methods should be said to provide an index of the biodegradability of the Organic Matter (OM) present in the studied water rather than a real value of the amount of the OM effectively biodegraded during the test.

BDOC methods do not have the disadvantages listed above. Indeed, the direct measurement of the decrease of the DOC during the test:

- avoids the use of arguable conversion factors and calibration curves,
- takes into account all the organic carbon metabolised by the bacteria to produce new cells (and not only considers the amount of the organic carbon corresponding to the maximum of growth),
- refers both to the growth and to the survival of the bacteria.

Nevertheless, similar patterns could be found for the evolutions of the BOM described by these different methods as a cause to effect relation exists between the decrease of DOC and the potential of the water to support bacterial growth. This presumes of a partial overlap of the BOM expressed as BDOC by the BOM expressed as AOC.

However, there is a lot of other reasons to prefer a BDOC method:

- BDOC methods only involve natural bacterial inocula coming from river water or sand from sand filters. This choice provides a better simulation of the reality of the water treatment plants and distribution systems than could do pure strains. Moreover, a natural mixture of bacteria is more likely to be able to biodegrade a wider variety of organic molecules.

Pure strains are susceptible to contaminations by other micro-organisms and their use is time-consuming and requires the previous sterilisation of the samples to be analysed which can alter the final result. Furthermore, round-robin trials carried out by Professor J C Block have shown that the origin of the natural inocula is not the major reason of the overall variability (< 25%) of the results obtained by different laboratories,

- the measurement of a DOC concentration is easy, quick and does not require unusual lab equipment or expensive reagents. The overall procedure seems easier to carry out (chemical and not biological determination),
- the use of a DOC unit makes the understanding of the BDOC results easy and those ones can be directly parallel to the DOC values measured along treatment or distribution,
- BDOC methods allow the estimation of the Refractory Dissolved Organic Carbon present in water.

In conclusion, the use of BDOC methods seems to be more suitable, based on theoretical and practical considerations, and these methods also seem to lead to an easier standardisation as they are more likely to be used in routine.

Furthermore, it should be underlined that:

- BDOC measurements are carried out in Europe (France, Belgium, Spain) and North America (Canada and USA),
- BDOC methods have been submitted to international round-robin trials (seventeen laboratories involved) to assess their performance,
- two BDOC methods are to be pre-standardised in France by the end of the year,
- a BDOC method should be included in the next edition of the American Standard Methods.

At this time, two BDOC methods have been developed and studied for several years. The first one was developed by Servais and Billen (University of Brussels - Belgium). It uses suspended bacteria and provides the BDOC results within four weeks. The second one was developed by Joret and Lévi (Anjou Recherche, Research Centre of Compagnie Générale des Eaux - France). It uses fixed (sand attached) bacteria and provides the BDOC results within a week.

It should be emphasised that these two methods are both used at the present time and that even the Committee in charge of French standardisation has not made any choice as yet.

However, the method of Joret and Lévi, due to the shorter response time required and to the higher BDOC values provided (which is beneficial when slight changes in the BDOC are to be considered, in particular in distribution) is the one which will eventually be selected.

This method has been used:

- to assess the BOM removal efficiency of different water treatment stages (including ozonation, GAC filtration and rapid or slow sand filtration),
- to study the evolution of the water quality in distribution,
- to build a predictive model of the occurrence of coliform failures in distribution (Anjou Recherche).

Finally, we must keep in mind that, in parallel with the improvement of the existing methods, new BDOC methods are being developed to try to obtain the BDOC results in a few hours, thus allowing process control.

2. Parameters Affecting the Drinking Water Quality in Distribution

A distribution system is a biological reactor receiving a discontinuous flow of organic matter, oxidant (chlorine generally) and cells, systematically leading to the formation of a microbial ecosystem, called "biofilm", at the solid-liquid interface and to the modification of the characteristics of the distributed water. Indeed, the biofilm formation and development are linked to the decrease of the Biodegradable Organic Matter (BOM) and the residual oxidant present in water and its tearing off results in the increase of the microbiological contamination of the distributed water.

The development of the biofilm is affected by many factors (such as: temperature, residence time and velocity of the water in the mains, nature of pipes), the evolution of which is complex and sometimes unpredictable. However, the biofilm formation may be slowed down by acting on the amounts of oxidant, organic matter and cells entering the distribution system.

2.1 Oxidant

At the present time, in most cases, a noticeable and constant effect on the micro-organisms present in the distributed water is expected from the application of an oxidant in post-disinfection (chlorine or chloramines). However, generally the oxidant is rapidly consumed in distribution. Moreover, a pilot study showed that a constant residual chlorine concentration of 0.5 mg Cl₂/l was necessary to kill the cells (measured as colony forming units - CFU) present in water but this residual did not prevent the accumulation of a biofilm on the surface of the pipes (DOC of the water at the end of the treatment = 1.0 to 2.0 mgC/l). A statistical estimation showed that a constant concentration of chlorine of 1.8 mg Cl₂/l would be necessary to prevent the biofilm formation. The same study demonstrated that chlorine is two times more effective than chloramines to kill the cells (CFU) in water and five times more effective to prevent the biofilm development. Furthermore, the micro-organisms present in the biofilm are protected against the disinfectant.

As the effective levels of residual oxidant cannot be reached in distribution without leading to negative side-effects on the water quality (bad tastes and odours, mutagenic activity) and as the unavoidable decay of this residual oxidant will leave some areas unprotected, it thus appears that the control of the bacteriological quality of the water in distribution cannot rely only on an increase of the oxidant dosage. Consequently, rather than fighting against the effects of the biofilm development, it would be judicious to try to prevent the biofilm formation. The improvement of the microbiological stability of the distributed water then requires the control of the "nutritional quality" of the water ie requires to lower the amount of BOM entering the distribution system.

2.2 Biodegradable Organic Matter

If some threshold values have been suggested for the Biodegradable Dissolved Organic Carbon (BDOC = 0.5 or even 0.2 mg C/l), the pilot study mentioned above showed that, in the absence of residual oxidant, a bacterial growth occurs with as little as 0.1 mg C/l of BDOC. However that may be, it should be kept in mind that any BOM entering the distribution system is likely to lead, at one moment or another, to a bacterial growth. Finally this bacterial growth is not prevented by high residual oxidant levels but is exacerbated by even low concentrations of BOM.

Thus, the search for an optimal scheme between the minimal concentrations of BOM and residual disinfectant still remains a primary objective. This optimal scheme will also be beneficial in respect of chlorine side-effects by lowering the concentrations of by-products precursors.

2.3 Micro-organisms

It was shown that even in the presence of residual oxidant (in the study considered - 0.4 mg Cl₂/l or 1.0 mg NH₂Cl/l) a biofilm forms by the deposition and the adsorption on the surface of the pipes of the cells brought by the treated water entering the distribution system; in the same pilot study, a relationship was found between the concentrations of cells leaving the treatment plant and the density of cells in the biofilm.

The present drinking water treatment lines are not designed to achieve a complete removal of the cells but reducing the number of cells leaving the treatment plant would undoubtedly slow down the biofilm development and its subsequent tearing off.

3. Drinking Water Quality Modelling

Strictly speaking, the density of micro-organisms present in the distributed water cannot be predicted for the good reason that it essentially depends on the tearing off of the biofilm which is an unpredictable phenomenon. However, it is obvious that the micro-organisms density in water is affected by all the factors which influence the biofilm growth (temperature, Biodegradable Organic Matter (BOM), residual chlorine). Thus, a predictive model of coliform occurrences is being developed at Anjou Recherche. This model is based on the following parameters: temperature, BDOC consumption between the treatment plant and the sampling point considered and the number of cells in water (epifluorescence microscopy counts).

Mathematical models are being elaborated to explain the removal of the biodegradable part of the organic matter in distribution. These models rely on physical (temperature, surface and volume of the pipes, water velocity, reversible adsorption of the cells), chemical (residual oxidant concentration, DOC level) and biological parameters (bacterial hydrolysis, growth and death of planktonic and fixed micro-organisms, epifluorescence microscopy counts).

The removal of the BOM in distribution is linked to the water retention time inside the network. Thus, the modelling of drinking water quality must take into account the age distribution of the water which can be achieved by a previous hydraulic modelling of the studied distribution network. This hydraulic modelling would be helpful not only to interpret the chemical and biological analyses but also to choose relevant sampling points on the network. One may think that a quite valid prediction of the areas of the distribution system where the biofilm may preferentially form and lead to problems could be obtained by the knowledge of the areas where a low water velocity and a significant decrease in BDOC are observed.

4. How to Avoid the Negative Effects of the Biofilm

As the formation of a biofilm in drinking water mains cannot be prevented, its development must be slowed down to avoid its subsequent negative effects.

The conditions of distribution affect the drinking water quality. Not only the hydraulic conditions are involved (retention time and velocity) but also the degree of maintenance of the mains. A great attention is paid by the French Water Companies to establish diagnoses of the state of cleanliness of the distribution systems and remedial actions are subsequently taken when necessary.

However that may be, the evolution of drinking water quality in distribution is greatly dependent on the quality of the water leaving the treatment plant. A study was carried out in the City of Laval by the Polytechnic School of Montreal (Quebec) to assess the impact of the degree of quality of the treated water versus the effect of the distribution conditions.

The evolution of the drinking water quality in distribution cannot be controlled without considering the efficiency of the treatment to remove the BOM present in the raw water. To improve this removal, two means may be considered. Firstly, the optimisation of the existing treatment lines (mainly the coagulation and flocculation steps); secondly, the use of new treatments. In this last case, the treatment including an ozonation followed by a GAC filtration has proved to be effective in many cases. In places where slow sand filters are used, good removals have also been obtained by the ozonation of the water before its filtration.

Finally, the nanofiltration process seems to be, at least in its principle, an ideal treatment. Indeed, it combines the removal of the BOM (subsequent to the removal of the DOC) to the removal of the cells. Moreover, due to the high degree of treatment expected from this process, the nanofiltration may replace both the ozonation, GAC filtration and post-disinfection steps. This process, still in its development phase, carries the hope of drinking water producers to provide and distribute a non-chlorinated drinking water (in places where chlorine had previously to be used) thus avoiding all its possible negative side-effects.

R E F E R E N C E L I S T

- BABLON G., VENTRESQUE C. and ROY F., 1987, Evolution of organics in a potable water treatment system, Aqua, 2, 110-113.
- BLOCK J.C., HAUDIDIER K., PAQUIN J.L., MIAZGA J. and LEVI Y., 1992, Biofilm accumulation in drinking water distribution systems, Biofouling (to be published).
- BRYERS J.D. and CHARACKLIS W.G., 1982, Processes governing primary biofilm formation, Biotechnol. Bioenging., 24, 2451-2476.
- BRYERS J.D., 1987, Biologically active surfaces : processes governing the formation and persistence of biofilms, Biotechnol. Progress., 3, 57-68.
- CHARACKLIS W.G. and MARSHALL K.C., 1990, Biofilms, John Wiley & Sons, Eds., U.S.A., Wiley interscience publication.
- De LAAT J., DORE M. and MALLEVIALLE J., 1991, Influence d'une préozonation sur l'absorbabilité et la biodégradabilité des substances humiques d'origine aquatique et sur les performances des filtres de charbon actif en grain, Wat. Res., 25, 151-164.
- HAUDIDIER K., PAQUIN J.L., FRANCAIS T., HARTEMANN P., GRAPIN G., COLIN F., JOURDAIN M.J., BLOCK J.C., CHERON J., PASCAL O., LEVI Y. and MIAZGA J., 1988, Biofilm growth in a drinking water network : a preliminary industrial pilot-plant experiment, Wat.Sci.Technol., 20, 109-115.
- HUCK P.M., 1990, Measurement of biodegradable organic matter and bacterial growth potential in drinking water, J.Am.Water Works Assoc., 82, 78-86.
- JANSSENS J.G., MEHEUS J. and DIRICKX J., 1984, Ozone enhanced biological activated carbon filtration and its effect on organic matter removal, and in particular on AOC reduction, Wat.Sci.Technol., 17, 1055-1068.
- JORET J.C. and LEVI Y., 1986, Méthode rapide d'évaluation du carbone éliminable des eaux par voie biologique, Trib. Cebedeau, 39, 3-9.
- JORET J.C., LEVI Y., DUPIN T. and GILBERT M., 1988, Rapid method for estimating bioeliminable organic carbon in water, Proceedings of the AWWA Annual Conferences, AWWA, Denver, Co., U.S.A., 1715.
- JORET J.C., LEVI Y., PAILLARD H. and RAVANINI P., 1989, Comparison of different full scale drinking water treatment plants for removal of biodegradable dissolved organic carbon, Proceedings of the AWWA Annual Conference, Los Angeles, U.S.A., 18-22 June 1989.
- KEMMY F.A., FRY J.C. and BREACH R.A., 1989, Development and operational implementation of a modified and simplified method for determination of assimilable organic carbon (AOC) in drinking water, Wat.Sci.Technol., 21, 155-159.
- LAWRENCE J.R. and CALDWELL D.E., 1987, Behaviour of bacterial stream population within the hydrodynamic boundary layers of surface microenvironments, Microb.Ecol., 14, 15-27.

- LECHEVALLIER M.W., SCHULZ W. and LEE R.G., 1991, Bacterial nutrients in drinking waters, Appl.Environ.Microbiol., 53, 2714-2724.
- LEVI Y., 1990, Importance du contrôle du Carbone Organique Dissous Bioéliminable (CODB) dans la stratégie de maintien de la qualité de l'eau potable en cours de distribution, in the Proceedings of the AQTE Conference, Montreal, Quebec, 16 November 1990, 635-644.
- LEVI Y. and JORET J.C., 1990, Importance of bioeliminable dissolved organic carbon (BDOC) control in strategies for maintaining the quality of drinking water during distribution, AWWA Technology Conference Proceedings "Advances in water analysis and treatment", San Diego, Ca. U.S.A., 1267-1279.
- MATHIEU L., BLOCK J.C., HARTEMANN P. and COLIN F., 1991, Paramètres contrôlant la prolifération des bactéries dans les réseaux de distribution : approche expérimentale, International Seminar "Biodegradable organic matter in drinking water distribution systems", Nancy, France, October 1991.
- SERVAIS P., BILLEN G. and HASCOET M.C., 1987, Determination of the biodegradable fraction of dissolved organic matter in waters, Water Res., 21, 445-450.
- STANFIELD G. and JAGO P.H., 1987, The Development and Use of a Method for Measuring the Concentration of Assimilable Organic Carbon in Water, Report PRU 1628-M, Water Research Centre, Medmenham, UK.
- TRULEAR M.G. and CHARACKLIS W.G., 1982, Dynamics of biofilm processes, J.Wat.Poll.Control Fed., 54, 1288-1301.
- VAN der KOOIJ D., VISSER A. and HIJNEN W.A.M., 1982, Determining the concentration of easily assimilable organic carbon in drinking water, J.Am.Water Works Assoc., 74, 540-545.
- VAN der KOOIJ D., 1986, The effect of treatment on assimilable organic carbon in drinking water, Proceedings of the conference on Treatment of drinking water for organic contaminants, Edmonton, Canada.
- VAN der KOOIJ D., 1990, Assimilable organic carbon (AOC) in drinking water, in Drinking water microbiology, Chapter 3, 57-87, Mc Feters G.A., Ed., Springer-Verlag, New York, U.S.A.
- VAN der WENDE, CHARACKLIS W.G. and SMITH D.B., 1989, Biofilms and bacterial drinking water quality, Wat.Res., 23, 1313-1322.
- VENTRESQUE C., BABLON G. and JADAS-HECART A., 1991, Ozone : a means of stimulating biological activated carbon reactors, Ozone Sci.Eng., 13, 17.
- WEBER W.J.Jr., and SMITH E.H., 1986, Removing dissolved organic contaminants from water, Environ.Sci.Technol., 20, 970-979.
- WERNER P., 1985, Eine Methode zur Bestimmung der Verkeimungsneigung von Trinkwasser, Von Wasser, 65, 257-270.

