ASBESTOS IN DRINKING WATER
VOLUME 1 (Main Report)
Contract Report to the Department of the Environment
July 1977 - March 1982

Project Leader: R.F. Lacey
Author: Deirdre M. Conway

November 1982
426-M

RESTRICTION: This report has the following restricted distribution:

External: DOE Nominated Officer - 16 copies
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SUMMARY

Before this project there was no information, that would now be considered reliable, about the concentrations of asbestos present in UK water supplies. Although the possible effects on health of exposure to asbestos via ingestion are at present very unclear, the general concern about asbestos was the reason for investigating its presence in drinking water.

This research was carried out under contract to the Department of the Environment, during the period from April 1977 until March 1982. The work was directed towards three main objectives:

(a) to evaluate methods of sampling and measurement of asbestos in water,

(b) to determine the concentration and types of asbestos in raw and treated waters in the UK,

(c) to determine whether and in what circumstances the use of asbestos-cement pipes can contribute to asbestos levels in the consumer's supply.

Objective (a) has been achieved and previously reported (WRC Technical Report TR 100). As a consequence of that work the asbestos analyses for the following survey were sub-contracted to the Ontario Research Foundation in Canada, the same laboratory as is used by the Canadian Government and by the US Environmental Protection Agency for similar work. The methods of sampling and analysis used in this project therefore allow comparison with the latest surveys from N. America.

The survey of asbestos concentrations in UK waters comprised the examination of 144 samples from a total of 65 carefully chosen locations at different stages of supply. The results of these provide the basis for reporting on (b) and (c). The results
suggest that most drinking waters in the UK contain asbestos fibres in a range from 'not detectable' up to 1.5 million fibres per litre (MFL). These levels are similar to typical levels observed in N. America and are low compared with levels in areas where asbestos is present in the local rock, particularly where it is mined.

The concentrations of amphibole asbestos found in UK drinking waters were mostly less than 1 MFL. For chrysotile asbestos only 12 of the 82 samples representative of potable water contained more than 1 MFL and only four samples (three locations) contained more than 3 MFL. 95% of all the fibres counted were less than 2 \( \mu \text{m} \) in length.

Levels of amphibole asbestos in potable samples drawn via asbestos cement pipe systems were higher than elsewhere but still low. Levels of chrysotile asbestos in such samples were all less than 1.5 MFL with the exception of four samples (three locations). Samples taken after deliberately disturbing deposits in asbestos cement pipe systems, however, mostly contained much higher levels, up to 58 MFL.

Three subjects were identified which may require further investigation: the use of asbestos cement tanks for potable water storage, the use of asbestos rope and graphite/asbestos rope in domestic plumbing, and the extent and effect on water supplies of asbestos waste disposal to land.
PREFACE

On 1st April 1977 the Department of the Environment placed a contract (Ref: DGR/480/353) with the Water Research Centre to investigate asbestos levels in drinking water in the UK. This contract ended on 31st March 1979 but was renewed for two years (Phase II) beginning on 1st April 1979 and ending on 31st March 1981 (Ref: DGR/480/617). There was a further extension of the work (Phase III) which began on 1st April 1981 and ended on 31st March 1982 (Ref: PECO 7/7/09).

Throughout Phases II and III, the determination of asbestos in water was undertaken at the Ontario Research Foundation under sub-contract to the Water Research Centre.

This is the final report of the work covering the period from April 1977 to March 1982.
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1. INTRODUCTION AND OBJECTIVES

In 1977 the Health and Safety Commission's Advisory Committee on Asbestos, which was examining environmental as well as occupational aspects of asbestos, recommended that the concentrations of asbestos in air and drinking water should be monitored. At that time there was no reliable information on the levels of asbestos in drinking water in the United Kingdom. The Department of the Environment (DOE) therefore placed a contract with the Water Research Centre (WRC) to undertake the survey described in this report. To begin with the objectives were:

(i) to evaluate sampling and sample preparation techniques for their use in studying levels of asbestos in drinking water in the United Kingdom,

(ii) to determine the concentration and types of asbestos in raw and treated waters in the United Kingdom,

(iii) to make an assessment of the effectiveness of existing water treatment methods in removing asbestos.

Work on the contract began in July 1977 but achievement of the first objective took longer than expected and the survey itself did not begin until early in 1980. The original contract which had run for just two years up to March 1979 was renewed for a further two years until March 1981 and again extended for one year until March 1982, to enable the completion of work towards objectives (ii) and (iii).

Before giving the results of the survey, this report describes the background to the work, including the mineralogy and usage of asbestos and the routes by which asbestos can enter the water cycle. The possible health effects of asbestos ingestion (i.e. asbestos absorbed via beverages and food) are also discussed.

The survey itself can be regarded as divided into two halves. The first part was exploratory and included some samples from 'typical' water supplies, where the asbestos levels were not expected to be different from the background, and other samples where the levels might be elevated. After assessing the results from the first half, WRC and DOE jointly decided that the second part of the survey should try to determine whether and in what circumstances the use of asbestos in the distribution system contributed to asbestos levels in water. The results of both parts of the survey are described.
2. ASBESTOS: MINERALOGY, PROPERTIES, APPLICATIONS AND WORLD PRODUCTION

2.1. MINERALOGY

The term 'asbestos' is derived from Greek meaning unquenchable or inextinguishable. It was probably used by the ancient Greeks to describe a material which could not be destroyed by fire. It was not applied to a mineral until the middle of the 19th century. Today asbestos is a collective mineralogical term that is applied to the fibrous forms of various hydrated silicate minerals. These minerals exhibit a variety of crystal habits depending on the physical conditions at the time of their formation. The term 'asbestiform' refers to a special type of fibrous habit in which the fibres have high aspect (length/width) ratios, are easily separable, are flexible and possess a higher tensile strength than crystals in other habits of the same mineral.

Asbestiform silicates can be divided into two groups on the basis of their structure. The fundamental unit in the building of silicate minerals is the SiO₄ tetrahedron in which the silicon atom (cation) is situated at the centre of a tetrahedron whose corners are occupied by four oxygen atoms (anions) (Figure 2.1a). When each SiO₄ tetrahedron shares two of its oxygen atoms with tetrahedra on either side a chain structure is formed (Figure 2.1b). When two single chains are placed side by side with the apices of the tetrahedra all pointing one way and are linked by sharing oxygen atoms at regular intervals, a double chain is formed (Figure 2.1c). These double-chain silicates are known as inosilicates and the amphibole group of minerals all possess this basic structure (1). All varieties of asbestos with the exception of white asbestos (chrysotile) belong to the amphiboles. The chains are linked together by cations, oxygen ions and hydroxyl ions. Some of the oxygen atoms in the tetrahedra may be replaced by hydroxyl ions. The type of mineral formed depends on which cations are present. Extensive substitution of cations by others of similar size and charge may take place so that there is a great variety of composition in the amphiboles. Some amphibole minerals form series. Such series have a range of variable cation ratios between two end members. An example of an asbestos series is the tremolite/actinolite series. Tremolite is the magnesium end member. Magnesium may be substituted by iron in a whole series of ratios up to 80%. The other end member, actinolite, has 80% of the magnesium ions substituted by ferrous ions (2).

The only non-amphibole asbestos is chrysotile, which is a fibrous form of serpentine. Serpentine is a phyllosilicate. Phyllosilicates have a sheet structure formed when the SiO₄ tetrahedra are linked by three of their corners and extend indefinitely in a two-dimensional sheet (1). (Figure 2.1c). In serpentine the tetrahedral silicate layer alternates with an octahedral magnesium hydroxide (brucite) layer and these layers are stacked, one on top of the other. The brucite layer has slightly
Fig. 2.1. Structure of asbestos minerals

a) A silicon tetrahedron – fundamental unit in the building of asbestos minerals

Silicon atom
Oxygen atom
Silicon-oxygen atomic bond

This simplified shape represents a silicon tetrahedron with its apex pointing out of the page.

b) A single chain of silicon tetrahedra

c) A double chain of silicon tetrahedra – silicates with this basic structure are known as inosilicates. Amphiboles are inosilicates and have a characteristic crystal structure containing parallel double chains of tetrahedrally co-ordinated silicon and bands of octahedrally co-ordinated cations.

d) A sheet of silicon tetrahedra – silicates with this basic structure are known as phyllosilicates. Chrysotile (fibrous serpentine) is the only asbestos mineral with this structure. In Chrysotile the silicate layer alternates with a layer of brucite (octahedrally co-ordinated magnesium hydroxide).
larger dimensions than the silicate layer. This mis-match is resolved in chrysotile by the curving of the sheet into a scroll or coil form, with the magnesium octahedra on the outside of the curve. The morphology of chrysotile allows it to be easily differentiated from other forms of asbestos under the electron microscope.

The preceding description of the asbestos minerals is based on crystallographic analyses of minerals of the same composition but of non-asbestiform habit. It is fair to say that at an atomic level the structure of asbestos is not fully understood and the explanation given is much simplified (3). The important asbestos minerals are listed in Table 2.1.

2.2. PROPERTIES

The most valuable properties of asbestos are physical ones resulting from its fibrous form. It has a high tensile strength and its surface area can be controlled within critical limits for a particular application. This latter property is what makes it so useful to industry: fibres of asbestos can be 'opened' or split, the degree of fiberisation or openness depending on the intended use. For example, the fibre dimensions required by the textile industry are quite different from those required by the asbestos cement manufacturers or the makers of brake and clutch linings (3).

Its most widely appreciated property is its resistance to heat and fire, although this resistance is not as great as is popularly believed. It is incombustible and has a low thermal conductivity. It therefore has numerous applications in fire prevention and insulation especially since certain grades of fibre may be woven into fire-proof cloth (4).

All types of asbestos are resistant to attack by alkalies at least up to 100°C. Resistance to acids is variable, depending on the acid and the chemical structure of the asbestos type. Chrysotile is rapidly decomposed by all acids as the outer magnesium hydroxide layers are stripped away. Amphiboles are much more resistant.

The structural differences between chrysotile and the amphiboles also affect their activities in water and in biochemical media. The isoelectric point of chrysotile in water is at pH 11.8. Below this pH it has a positive charge; above it, it has a negative charge. Most dispersed materials in aqueous systems have a negative surface charge. Thus chrysotile attracts or is attracted to most dispersed material. The isoelectric point of the amphiboles is around pH 6. Therefore in most aqueous systems amphibole fibres are negatively charged.
<table>
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<tr>
<th>Silicate structure</th>
<th>Mineral group</th>
<th>Mineral variety</th>
<th>Major cation(s) linking silicate structures</th>
<th>Present and past mining locations</th>
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<tr>
<td>Sheet (phyllosilicate)</td>
<td>Serpentine</td>
<td>chrysotile</td>
<td>$\text{Mg}^{2+}$</td>
<td>Canada - E. Quebec, British Columbia, Yukon;</td>
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<tr>
<td></td>
<td></td>
<td>(white asbestos)</td>
<td></td>
<td>Russia - Urals, E. Siberia;</td>
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<td></td>
<td></td>
<td></td>
<td>Africa - Zimbabwe, Swaziland; CS - Vermont,</td>
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<td>Arizona; and China</td>
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<td>Double chain</td>
<td>amphibole</td>
<td>crocidolite</td>
<td>$\text{Na}^+ \text{, Fe}^{3+} \text{, Mg}^{2+}$</td>
<td>S.Africa - Cape Province, Transvaal;</td>
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<td>(inosilicate)</td>
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<td>(blue asbestos)</td>
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<td>Australia; Bolivia and Zambia</td>
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<td>anthophyllite</td>
<td>$\text{Mg}^{2+} \text{, Fe}^{2+}$</td>
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<td></td>
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<td>tremolite/actinolite</td>
<td>$\text{Ca}^{2+} \text{, Mg}^{2+}$</td>
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<td></td>
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<td>series(2)</td>
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<td>Taiwan, S. Africa - Cape Province</td>
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<td></td>
<td></td>
<td>(a) tremolite</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>(b) actinolite</td>
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<td>grunerite series(3)</td>
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<td></td>
<td>(a) cummingtonite</td>
<td>$\text{Mg}^{2+} \text{, Fe}^{2+}$</td>
<td>S. Africa - Transvaal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(b) grunerite(4)</td>
<td>$\text{Mg}^{2+} \text{, Fe}^{2+}$</td>
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</table>

(1) These cations are combined with O and OH ions in the crystals

(2) Tremolite and actinolite are end members of a mineral series. Tremolite is the pure magnesium end member. In the other end member, actinolite, 80% of the magnesium has been substituted by iron.

(3) Members of this series are identified by Fe/Mg ratios. The relative proportions of magnesium and iron vary from $\text{Mg:Fe} = 7:3$ to all Fe. Cummingtonite has an Mg/Fe ratio greater than 1, grunerite has more Fe than Mg - and ranges up to all Fe.

(4) Amosite (brown asbestos) is not a generic term but comes from 'Association of Mines of South Africa'. Amosite is usually predominantly (95%) grunerite with some actinolite. It has occasionally been used for anthophyllite (1).
2.3. WORLD PRODUCTION AND USE IN BRITAIN

The present world-wide annual production of asbestos is more than 5 million tonnes. Most (93%) of this is chrysotile and three-quarters of it is mined in Russia and Canada, which in 1979 produced 2.4 million tonnes and 1.5 million tonnes respectively. Both these deposits are very similar and are located in serpentinised rocks. The Russian chrysotile is in the Central and Southern Urals and the North American deposits are in the Appalachian mountains in southeast Quebec and northern Vermont (6,7).

The mining of amphibole asbestos is now confined to South Africa. Other deposits which have been worked in the past are given in Table 2.1.

Russia exports only 18% of its asbestos. Canada, however, exports 97% of the asbestos it produces and is therefore the most important world supplier. The U.S.A. is the largest importer (more than 0.5 million tonnes in 1979) followed by West Germany (0.4 million tonnes) and Japan (0.3 million tonnes) (6).

Asbestos imports into the United Kingdom peaked in 1973 at 171,000 tonnes (Figure 2.2) after which doubts about its safety began to have a serious impact on its usage. In Britain to-day more than 40% of imported asbestos is used in the asbestos cement (A/C) industry with other significant uses being friction materials, jointings and packings, textiles, floor tiles, paper, felts, fillers, reinforcements and fire-resistant insulation board. Although many scientists believe that with proper control asbestos may be used safely, the pressure to find substitutes is very great. In 1981 there were 200 new patents issued for asbestos products but over a 1,000 for substitutes.

3. ASBESTOS IN DRINKING WATER: POTENTIAL SOURCES IN THE UNITED KINGDOM

Asbestos is a ubiquitous mineral, far more so than is generally realised. Ambient levels in drinking water vary between 100,000 fibres per litre and 1.5 million fibres per litre (MFL) (8,9). Most of these fibres are visible only with an electron microscope at magnifications of 20,000 times. Reliable information on the actual levels in drinking water is not generally available. This is because the analysis of water samples for asbestos is complicated and expensive, and the methodology is still developing (to the extent that only data from 1979 onwards are now considered to be reliable). Consequently there have been very few comprehensive surveys of asbestos in drinking water with the exception of work in the late 1970's, in the US and Canada (8,9). These surveys suggest that more than 90% of fibres found in drinking water are <5 μm in length.
Fig. 2.2 Metric tonnes of chrysotile imported into the UK 1880–1979 (5,6)
Asbestos may enter the water cycle directly as a result of natural erosion processes of asbestiform minerals, the corrosion of asbestos materials in the distribution system or direct discharge of asbestos waste to water or sewer. It also enters the cycle indirectly as a result of industrial activity. Once released to the environment, asbestos by its nature is persistent and may be dispersed over wide areas in air and water. The only irreversible sink is water.

3.1. NATURALLY-OCCURRING ASBESTOS MINERALS

Although there are some isolated outcrops of asbestos minerals in Britain none are commercially exploited although they may have been in the past. The DOE commissioned a report from the Institute of Geological Sciences (IGS) on the occurrence of asbestiform minerals in Britain. It was reported that none of these outcrops were likely to have serious impact on water supplies (10). Outcrops of chrysotile and tremolite have been identified in Snowdonia, Caernarvonshire, Cornwall, Hereford, Aberdeenshire, Banffshire, Invernesshire, Skye, Sutherland, Guernsey and Jersey (11). Two samples taken from surface waters close to an asbestos outcrop in Scotland in 1977 as part of the pilot study for this project did not show elevated levels of asbestos. The analytical method used would, however, today be considered inadequate.

3.2. INDUSTRIAL ACTIVITY

Contamination of the environment by asbestos fibres can occur at the point of extraction, manufacture, product use and disposal.

Surveys of asbestos levels in drinking water in the U.S and Canada demonstrate that the highest levels found (up to 1200 MFL) are associated with mining (8,9). There are no mining operations in Britain.

Emissions from manufacturing sites are static and are tightly controlled by legislation. The present limits for concentrations of chrysotile and amosite in air are 2.0 fibres/cm³. The limit for crocidolite is 0.2 fibres/cm³ which is effectively a ban on its use. These levels were set in 1969. More recently the Advisory Committee on Asbestos (ACA), in its final report (12), recommended that the level for chrysotile be reduced to 1.0 fibres/cm³ and for amosite to 0.5 fibres/cm³ and for crocidolite remaining at 0.2 fibres/cm³. However, the proposed European Community Directive has set the levels for both chrysotile and amosite at 1.0 fibres/cm³ and the ACA have accepted this. This legislation is not yet in force but most of the manufacturing industry already complies with it.
Emissions at the point of use and waste disposal are the hardest to quantify in terms of air and water pollution. The construction, renovation and demolition of buildings can give rise to emissions when asbestos materials are involved. Levels of asbestos in air have been shown to be higher where traffic is concentrated, due to the degradation of friction materials in brakes and clutches (13,14). Such exposures, while of short duration, may be quite high and are certainly several orders of magnitude above the background (15). The resultant waste from these products may also be a source of emission if improperly disposed of. This can arise from ignorance of the fact that the materials involved contain asbestos. All these emissions are diffuse and transient in nature and thus very difficult to quantify and control. It is not possible to examine or evaluate the effects of this type of emission on levels in drinking water in such a limited survey as this one.

In Britain, the correct procedure for the disposal of known asbestos waste is described in the DOE Waste Management Paper No. 18 (1977). The code of practice is non-statutory but it may be enforced by the waste disposal authorities. Prior to this, dumping and land-filling by the asbestos industry was less controlled and documented and there may be situations where water sources are polluted. This type of contamination is of direct concern to the water industry and so was investigated in the survey.

3.3. THE USE OF ASBESTOS PRODUCTS IN THE DISTRIBUTION SYSTEM

A variety of asbestos products are used in distribution systems in Britain. Most of these are asbestos-cement (A/C) products. In the 1930's A/C pipe became established as a low-cost, strong pipe which was eminently suitable for carrying water under pressure. Its use was popular in situations where soil and water were aggressive to other types of pipe. It is also a pipe material which, unlike cast iron, does not cause discoloration of water. Although the exact proportion of A/C pipe in British distribution systems is not known, it is generally estimated to be about one third of the total (16). About 10-15% of an A/C pipe by weight will consist of asbestos. Of the asbestos, 90% will be chrysotile and about 10% will be an amphibole, the exact proportions depending on the grade of fibre being used. Before the introduction of more stringent controls in this country in 1969 the amphibole, crocidolite, was used. This has now been replaced by amosite (17). Thus pipes more than 13 years old may contain about 3% by weight of crocidolite.

A/C sheeting is used to cover service reservoirs and A/C domestic storage tanks have been used for many years, particularly in public housing, because of their relative cheapness. Since the growing awareness of health effects in the 1970's, however, the demand for tanks has fallen (17).
A less-well known use of asbestos in distribution systems is as gaskets and packing in water pumps. Asbestos rope and graphite/asbestos rope are also used to pack pipe joints and tap-glands. The exact extent of these practices is unknown but they are common.

Asbestos materials in the distribution system may contribute directly to asbestos levels in drinking water. Use of these products is widespread and their safe handling and control are of particular interest to the water industry. It was therefore felt that the survey should pay particular attention to the contribution made by asbestos products in distribution systems to the levels in water, and the conditions under which release of fibre might occur.

4. HEALTH EFFECTS OF ASBESTOS WITH PARTICULAR REFERENCE TO INGESTION VIA DRINKING WATER

4.1. HEALTH EFFECTS OF ASBESTOS INHALATION

The health effects of inhaling asbestos in air for prolonged periods are well-documented (12,18,19) and the mechanisms have been the subject of extensive research for more than 20 years. Occupational studies show that prolonged exposure to asbestos is associated particularly with raised incidences of asbestosis, mesothelioma, lung cancer and gastro-intestinal (GI) cancers. Pleural mesothelioma and peritoneal mesothelioma, which are cancers of the lining of the chest and the abdomen respectively, are almost exclusively associated with asbestos exposure. Cigarette smoking and exposure to asbestos appear to act in a synergistic manner; the incidence of lung cancer being much higher among smokers than non-smokers who are occupationally exposed (20).

Despite an intensive research effort the pathogenesis of asbestos cancer at the cellular level is not understood. Research suggests that the occurrence of disease is influenced by the type of mineral (this includes fibre dimensions and surface properties), the concentration and duration of exposure, and the time since onset of exposure (latency). However, occupational epidemiology and animal experiments have produced inconsistent results. For example:

(i) Much animal work has shown that crocidolite produces more mesotheliomas than chrysotile but some good inhalation experiments have demonstrated that chrysotile is as dangerous (21).

(ii) The prevalence of mesothelioma in crocidolite miners in northwest Cape, South Africa is common but it is rare in the Transvaal where the fibres mined are coarser (19).
These contradictions are illustrated by national approaches to legislation. Britain considers that crocidolite is more dangerous than chrysotile and amosite, and this is reflected in our legislation (see section 3.2). The U.S National Institute of Occupational Safety and Health, however, stated in 1980, "On the basis of available information, the committee concludes that there is no scientific basis for differentiating between asbestos fibre types for regulatory purposes".

There is a widely-held belief that fibre dimension is the major aetiological factor in carcinogenic response. This view, 'Stanton's hypothesis', arose out of work done in the early seventies using mineral fibres of wide chemical and structural variety (22). Stanton found that long thin fibres, >8 μm in length and <0.25 μm in diameter, were most likely to cause tumours in animals. Fibres >4 μm in length and up to 1.5 μm in diameter also correlated, but to a lesser degree, with tumour incidence. However, in a later paper (23) Stanton observed that short fibres and large-diameter fibres were removed or inactivated by phagocytes, whereas phagocytosis of long thin fibres was negligible; and thus his experiments may simply be a measure of the efficiency of phagocytosis. All his samples contained particles in a wide fibre range but the frequency of long thin fibres in some samples was much higher than in others. He suggests that "What is perhaps more likely than the existence of a narrow range of sizes within which particles are carcinogenic and outside of which they are not, is that the probability of tumour falls as particle diameter increases and length decreases". Very recent work suggests that the primary determinants of biological activity of fibres are surface charge, solubility, specific surface area and fibre dimensions, and that "Fibre dimensions are important in determining whether asbestos fibres are able to reach sites where critical cellular interactions take place and thus could govern whether the potential biological activity of fibres, due to their surface charge, is displayed" (24).

There is much literature on this subject which it is impracticable to discuss here (21-28). However, an appreciation of the role of surface properties of fibres in their potential for biological activity is fundamental to understanding the contradictions in the literature. There is evidence that fibres (even of the same mineral type) used in different industries and mined in different locations have distinctive surface properties. In turn these are different from those of fibres used in animal experiments (27,28). It has also been suggested that the comminution methods used by Stanton and others to produce the various ranges of fibre-sizes, particularly short fibres, for their experiments, would have resulted in fibres with a reduced surface activity (26). Epidemiological evidence has shown that there is a marked difference in risk in various industries using the same
mineral fibres (20,29). The lowest risks are found amongst asbestos-cement workers, miners and millers, and the highest risks amongst textile and insulation workers. Amongst the last two groups, the risk appears to increase as the mineral is processed. The hypothesis that this is because the fibres have different surface activities is an attractive one.

Given the unresolved issues on health effects of asbestos inhalation the job of the legislator is very difficult. There is no good data on mortality patterns of workers exposed at or below the current permissible limit of 2 fibres/cm³. Thus this risk is estimated by extrapolating to low-levels a dose-response 'curve' developed from mortality data for workers exposed to high levels in the past. There is general agreement that this dose-response curve is a straight line (22,29). With the exception of asbestosis (for which there is evidence that incidence is proportional to cumulative dose), it is thought there is no threshold below which there is no risk from exposure. Risk extrapolation from retrospective epidemiological studies is beset with difficulties, such as estimating past exposure in the measurement units of current interest and determining the mortality experience of the group. The latter is affected by the quality of the records and the study design. However, it is generally held that good epidemiological work is preferable to animal bioassay work for quantitative cancer risk assessment. This is a point which should be borne in mind when considering the evidence for health effects of asbestos ingestion, as well as those of asbestos inhalation.

4.2. HEALTH EFFECTS OF ASBESTOS INGESTION

There are three sources of ingested asbestos: food, beverages and air. Beverages may be filtered through an asbestos filter (30), food and water may be contaminated (see section 3) and asbestos which is breathed in may be subsequently swallowed.

The evidence for an excess of GI cancers amongst asbestos workers is not as strong as for the other diseases and not all occupational studies have demonstrated an effect. However, several competent studies have shown GI effects, ranging from a moderate excess (31) to 2-3 times higher observed than expected incidence (32,33). Miller's comprehensive review of the literature concluded that there was a weak causal relationship between asbestos exposure and GI malignancies (34).

Inhaled asbestos is cleared from the lungs by the pulmonary clearance mechanism and swallowed. Estimates of the percentage of inhaled fibres which are subsequently ingested range from 73% to 98-99% (35,36). The crucial question is whether it is the inhaled or the ingested fibres which are responsible for the raised GI cancer incidence. Inhaled asbestos in lung tissue passes into the bloodstream and is then transported to distant sites including the
GI tract. Most biologists and some epidemiologists favour the inhaled route (28,37,38) and maintain that there is no health effect from ingestion. Some epidemiologists, however, believe that the evidence cannot be regarded as conclusive and the position on ingestion is unclear (39,40).

The arguments in favour of the inhaled route are:

(i) That the GI mucosa constitute an extremely effective barrier to inorganic particles and fibres (35-37).

(ii) The experimental evidence on ingestion is conflicting and this is reviewed by Bolton and Davis (35,41). Some studies do show fibre penetration while others do not (36). None of the studies have demonstrated a significant increase in malignant GI tumours. Recent high-quality animal work has not been able to demonstrate migration of fibres after prolonged ingestion (41).

(iii) Environmental epidemiological studies of asbestos in drinking water are mostly negative. GI incidence data for Duluth, Minnesota were compared with those for Minneapolis and St Paul, Minnesota for 1969-71 (42) and 1969-74 (43). Duluth receives its water from Lake Superior which since 1955 has been contaminated with mine tailings. The water contains up to 30 MFL amphibole asbestos. No significant associations were found but the study can be criticised because the latency period was only 14-19 years.

Studies of the association between use of A/C pipe and cancer incidence in Connecticut are also negative (44,45). Little A/C pipe was used before 1955 and thus the latency period in these studies is 19 years which is probably too short. In addition the levels of asbestos measured in the water were very low.

One study in California, however, has shown significant associations between asbestos in drinking water and various GI tract cancers (46). The sources of the asbestos is natural, most of the Californian country rock being serpentine. The study was updated in 1981 and a further three years cancer incidence data were added (47). The previous associations still held. This study may be criticised on a number of grounds, for example the regression models never explained more than 10% of the variance and often less than 3%.
For these reasons it is considered that there is unlikely to be a health effect from asbestos ingestion. Nevertheless other scientists believe that the evidence is still equivocal because:

(i) Although the GI mucosa is an effective barrier to inorganic particles, there are indications that some fibres may penetrate tissue. For example, amphibole fibres have been found in the urine of subjects who drank unfiltered Lake Superior water. When the subjects changed to filtered water (with lower asbestos levels) the amount of fibres found in urine was eventually reduced by more than 90% (48).

It is estimated that about 5% of humans may have areas of intestinal mucosal damage (49) and could therefore be at risk from ingested asbestos (41).

(ii) As discussed in section 4.1 the biological activity of asbestos fibres used in animal experiments may be quite different from that of fibres ingested. There are difficulties in extrapolating from animals to man and good epidemiological work is preferable to animal bioassay work for human cancer risk assessment (cf (iv) below).

(iii) Valid criticisms may be made of all the environmental epidemiological studies described in (iii) above. An excellent critical review of these, and other investigations in Canada has been produced by Wigle (50). He concludes that although one can be critical of certain aspects of the San Francisco Bay Area study the results should not be discounted because the work was very well designed.

The other investigations have common weaknesses. The latency period for humans, between exposure to asbestos and the onset of disease, is at least 20 years and often more than 30 years. Many of the studies are looking at exposure periods of less than 20 years. Also such a long latency period means that this type of study will tend to underestimate risk unless controls are included for the influence of population mobility (48). This has not been done. Dietary habits are an important factor in the aetiology of GI cancers; direct measures of this are not available (48). Occupational studies suggest that the risk of GI cancer is much less than the risk of other asbestos-related disease. It is doubtful whether these environmental studies are powerful enough to pick up such a small effect, especially when other major confounding variables are not controlled.
(iv) If one wished to estimate risk, the only way this can be done at present is to work from occupational data. One can estimate past exposure which led to the present GI cancer incidence rate. One can then define an arbitrary "acceptable risk" and work backwards to calculate the maximum acceptable exposure. This approach involves a number of assumptions. These assumptions and some examples of the calculations involved are described in Wigle's paper (50) and in the EPA criteria document for asbestos in water (51).

In addition to the assumptions described in these papers a number of other assumptions are made which should be mentioned. These relate to fibre characteristics. Fibres ingested in an occupational context are likely to be different from those in drinking water because the fibre size frequency distributions will be different. In the former case they will be across the respirable range. In drinking water the range will be different depending on the situation (e.g. the water may have been filtered, or have passed through asbestos-cement pipe or have been in contact with an asbestos rock). Also the chemistry of the water may profoundly affect the surface properties of the fibres. Whether such differences are significant to health cannot be determined until the mechanisms for asbestos carcinogenesis are better understood at cellular level.

5. CHOICE OF LABORATORY FOR SUB-CONTRACTING ASBESTOS ANALYSES

The analysis of drinking water samples for asbestos is highly specialised and time-consuming. Consequently it is also very expensive. When the project began in 1977 the first priority for WRC was to find a laboratory which could produce reliable results at a reasonable price, and which could cope with the volume of samples that would be generated by the main survey. It was also considered important that the laboratory chosen should use the method current in the United States which had been developed by the U.S Environmental Protection Agency (EPA) (52). This was because the EPA was considered to have the most experience of this type of analysis at that time and it was involved in assessing levels in American water. It was thought desirable to be able to compare the results of the limited British survey with the American data.

WRC therefore asked a number of British laboratories if they were interested in undertaking the work. Several laboratories had the facilities and the expertise to do the analysis but their own workload was sufficient for their resources. Other laboratories were interested in the contract but did not have the equipment necessary to use the EPA method. Eventually two consulting laboratories, the Laboratory of the Government Chemist (LGC) and the University of Manchester Institute of Science and Technology (UMIST), agreed to analyse a series of samples to test their precision and reproducibility and also to make an estimate of
costs. The laboratory at UMIST was experienced at water analysis and estimated their costs at £200 per sample. However, owing to other commitments the rate at which they could analyse samples was too slow for the main survey. The LGC had less experience but wished to develop this capability and were acquiring new facilities and staff to do so. They estimated their costs at about £100 per sample. Over a period of more than 18 months the WRC sent a series of samples to LGC to test their precision. It became apparent that LGC were having difficulty with the method. With the benefit of hindsight and a greater appreciation of just how difficult the analysis is, the problems which occurred were only to be expected.

It was at this time that the WRC decided reluctantly to look for a suitable laboratory overseas. On the recommendation of the Canadian Government's Environmental Health Centre in Ottawa, WRC approached the Ontario Research Foundation (ORF) in Toronto. ORF had extensive experience of environmental asbestos analysis, both in air and water. They had analysed water samples for the American government and had recently completed a national survey of asbestos in drinking water for the Canadian Government (9). In addition, in October 1978, they were awarded a 3 year contract by the US EPA to further develop the interim method of analysis for asbestos in drinking water. WRC sent a series of samples to ORF to test precision and was very satisfied with the results. It was clear from these and the manner in which the data were presented that ORF was very experienced in this work. The cost of the analysis per sample (including transport) was similar to that of LGC. ORF was therefore awarded the sub-contract and the first samples were sent to Canada in 1980. The results of the British survey are thus directly comparable with the North American work.

6. THE DETERMINATION OF ASBESTOS LEVELS IN DRINKING WATER

6.1. ANALYTICAL METHOD

The identification of asbestos fibres in water is difficult. A typical water sample contains a variety of minerals and organic debris. Mineral or diatomaceous fragments may be classified as asbestos if examined by techniques which do not incorporate any identification procedure. The relative merits of various methods of analysis of asbestos in drinking water are described in the WRC Technical Report "Asbestos in drinking water: A review" (11). The most powerful procedure employs a transmission electron microscope (TEM) coupled with selected area electron diffraction and energy dispersive X-ray techniques. This is the method used by ORF. It allows observation of morphology and it is capable of discriminating between different amphiboles.

The sample bottles were prepared at WRC. One litre polyethylene bottles and their caps were filled and soaked in 10% Analytical nitric acid for one week. They were then emptied and rinsed three times in deionised water. The rinsed bottles were filled
with double-distilled water and the caps replaced. They were placed in an ultrasonic bath for 15 minutes. After this they were emptied and rinsed twice with double-distilled water. The caps were replaced and the bottles were sealed with parafilm and stored in a clean, dark place until required. The parafilm was removed immediately before a sample was taken. The bottle was rinsed several times in the water being sampled and then filled about four-fifths full. Care was taken not to contaminate the cap during this procedure. Once the cap was replaced the bottle was resealed with parafilm. No preservatives were added to the samples. They were kept cool and in the dark and taken as soon as possible to London Airport for shipment to Ontario.

Asbestos is ubiquitous in the environment and contamination is possible at all stages of the procedure, from sample bottle preparation to microscope grid analysis. To allow for this, duplicate samples were taken at each site. After collection each batch of samples was recoded, using random numbers, before being dispatched to Canada. ORF were unaware that the samples for analysis included duplicates.

On arrival at ORF the samples were shaken in an ultrasonic bath to redisperse the asbestos fibres before an aliquot was taken for filtration. During the course of this survey, experimental work at ORF, showed that in unsterile samples, such as tap-water, micro-organisms scavenged asbestos fibres and attached them to the walls of the container. Shaking in an ultrasonic bath appears to enhance this effect. This may be overcome by bubbling filtered ozone gas through the liquid while irradiating the sample with ultraviolet light (UV) followed by 15 minutes of mild ultrasonic agitation (53,54). During the first part of the survey any sample in which significant levels of bacteria were observed was given ozone-UV treatment and reanalysed. For the second half of the survey this was done routinely for all samples.

The TEM grids were prepared by the direct carbon-coated Nucleopore technique recommended by EPA (55). A known volume of sample is filtered through a 0.1 μm pore size Nucleopore polycarbonate membrane. For each sample a range of volumes are filtered. A carbon film is applied to the filters by vacuum evaporation which traps all the particles on the filter surfaces. Sections of the filters are then mounted on TEM copper specimen grids and extracted in a Jaffe washer using chloroform as the solvent. The grids are scanned in the TEM to see what level of inorganic material is present. Where the level of particles is too high the grid will be overloaded and many of the particles obscured. Thus the grids with the most suitable density of particles are selected for examination. The larger the volume of sample which may be filtered without overloading the grid, the better will be the analytical sensitivity of the method (see section 6.2).
The selected grids are then examined systematically according to a procedure developed at ORF (56). (ORF defines a 'fibre' as a particle which has parallel or stepped sides and an aspect (length:diameter) ratio equal to or greater than 3:1, and is greater than 0.5 μm in length.) After an examination of the morphology of each fibre at magnifications around 20,000x, the crystal structure is obtained using selected area electron diffraction (SAED) and its elemental composition is obtained by energy dispersive X-ray analysis (EDXA). Asbestos particles are classified as either chrysotile or amphibole. Chrysotile can be identified on the basis of its characteristic tubular morphology (see section 2.1) with confirmation by SAED or EDXA. Amphiboles are identified using SAED and EDXA.

All aspects of the procedure from the preparation of sample bottles to specification of equipment and apparatus and presentation of results are given in the final report of ORF's 3 year contract from EPA, to develop the interim method of analysis for asbestos in drinking water (56). This report is presently going through the EPA review system and has not yet been published.

6.2. STATISTICAL ASPECTS

Despite the technical refinements described in the previous section, the determination of the concentration of asbestos in water is statistically very imprecise. The analytical method amounts to actually counting the number n of fibres that were present in a small volume v of the water sample submitted for test. The estimate of concentration in terms of fibres per litre is then obtained as n/v. In order to gauge the reliability of this result, the sampling error associated with the count n must be multiplied by the very large magnification factor 1/v.

The statistical aspects of this are discussed in full in the ORF report (56). For the purpose of the present report we repeat only enough to explain the statistical treatment adopted for later results.

The preparation of a water sample for asbestos counting involves the filtration of an original sample of volume v through a filter membrane of effective filtration area A_f (Figure 6.1). Let the total area of membrane examined under the electron microscope be A. This is determined by the grid size and the number of grid openings examined. The volume of water to which this area corresponds is

\[ v = VA/A_f \]

The physical characteristics of the filtration process and the size of area scanned for counting thus determine v.
'A' is the total area of grid openings examined. 'A_f' is the effective filter area. 
E.g., Number of fibres 'n' in the counting area is 3. Counting area corresponds to the number of grid squares 'k' which are examined (k = 4)

Fig. 6.1. Preparation of a water sample for asbestos counting
If exactly one asbestos fibre was seen in the area examined, it would lead to an estimate of fibre concentration of \(1/\nu\). This quantity, \(C\), will later be referred to as the fibre concentration which corresponds to a fibre count of one.

In general, the result of counting the fibres in area A will be \(n\) and, as previously stated, this yields an estimate of mean fibre concentration of \(n/\nu\). In order to place a measure of precision on this estimate it is necessary to make some statistical assumptions about \(n\).

6.2.1 Confidence Limits

a) Method 1. In view of the processes of agitation and dispersion used in sample preparation, the natural assumption to make, at least for smallish values of \(n\), is that \(n\) has arisen from a Poisson distribution of unknown mean, \(m\). If so then \(n\) itself is the best estimate of \(m\) and confidence limits for \(m\) can be obtained from standard tables (57). If \(m_A\) and \(m_B\) are the lower and upper limits at the chosen levels of confidence then the corresponding confidence limits for mean fibre concentration are simply

\[
\frac{m_A}{\nu} \text{ and } \frac{m_B}{\nu}.
\]

(or alternatively \(m_A/C\) and \(m_B/C\))

If \(n\) is larger than the extent of the statistical tables the above method can still be used by making one of the standard approximations to the Poisson distribution.

b) Method 2. Although the Poissonian assumption is the most useful one when fibre counts are low, the experience of ORF suggests that it is only approximate. If fibres are plentiful in relation to the area of filter that can be economically scanned, then it is possible to relax the Poissonian assumption and adopt a more detailed statistical treatment. This uses not only the total number of fibres, \(n\), counted over the area examined A but also the subtotals \(n_1, n_2, \ldots, n_k\) counted in \(k\) separate equal grid openings that constitute A (Figure 6.1). The sample standard deviation \(s\) of the \(n\) can then be used to estimate confidence limits for \(m\) the expected value of \(n\). These are

\[
n \pm \sqrt{k} ts,
\]

where \(t\) is the appropriate percentage point for the distribution of Student's \(t\) with \((k-1)\) degrees of freedom. Confidence limits for mean fibre concentration follow as before.
In the present report we provide confidence limits calculated by Method 1. This method is valid even if the count is zero and this is how the result of zero counts will be reported. The size of confidence intervals reported will always be two-sided 95%.

6.2.2. Limit of detection

Because the volume of water that corresponds to the area scanned by the electron microscope is minute, it is important to consider the lower limit of asbestos concentration that this analytical method is capable of detecting. The spirit of WRC Report TR 66 (58) is followed in defining the limit of detection as the minimum concentration, \( L \), for which there is an acceptably high probability that the determinand will be positively detected. It is usual in the U.K. water industry to set this probability at 95%. If this is done in relation to asbestos determination then, on the Poisson assumption mentioned earlier, the limit of detection is 3.00C where \( C \) is the concentration corresponding to one fibre counted. It is evident from this that the limit of detection can thus vary from one determination to another depending on the quantity of sample filtered and the area of membrane counted. This is common sense as the larger the volume, \( V \), that is scanned, so the smaller will become the limit of detection, \( L \), according to:

\[
L = 3.00/V
\]

The factor of 3.00 here is a consequence of the choice of 95% for probability of detection. This number is derived as \(-\log_\beta\) where \( \beta \) is the required probability of failure to detect; in this case 0.05.

6.2.3. Comparison of samples

In any survey which gives the results of sampling at different points, the question naturally arises whether the estimated concentration of asbestos in, say, sample A is significantly different from that in sample B. By 'significantly different' is meant that the numerical difference, between the estimates of fibre concentrations in the two samples, is greater than that which can plausibly be attributed to the statistical uncertainty inherent in the sampling and analytical process. In the context of the present study the question is of interest at two levels, first as a check on the consistency of results within each pair of duplicate samples and second as a test of genuine difference between concentrations at different sampling sites.

Fortunately it is straightforward to resolve these questions by means of a formal statistical test. If the estimates of fibre concentrations in the two samples are based on examining equal volumes then the significance of the disparity in observed counts may be judged directly (using Table 36 in reference (57)). If, as is usually the case, the volumes are unequal then a more general
approach is needed and several methods are available for this (59). A method was chosen which is the direct generalisation of Table 36 and this is provided by equation (2) or (3) given in reference (59).

The large degree of uncertainty in estimating fibre concentrations from small numbers of counted fibres has the consequence that comparisons between such estimates are of very low statistical power. The power of comparison is directly related to the effort available for counting and hence to the cost of the asbestos analysis.

Although the power of comparison between sites has turned out to be very low because of the low fibre counts, this could not have been predicted in advance of undertaking this study. The results of the present study would now provide a basis for the design of future work with specified power. The implications of such a requirement would almost certainly be an order of magnitude increase in the analytical effort required.

6.3. REPORTING OF RESULTS

On completion of the analysis of each batch of samples the ORF submitted a detailed report to WRC. These reports include a short summary of the results for that batch followed by detailed analytical data for each sample. As well as information about the concentration of asbestos in the sample and the number of fibres counted, this data includes information on volume of sample filtered, magnifications used, grid square dimensions, fibre length distributions and mass concentrations. The detailed analytical data for 2 samples have been reproduced in Appendix A. One sample (D16) has a low concentration of asbestos and the other (D14) a high concentration. Such a level of detail is not necessary for all the samples in this report. Usually the following parameters only will be reported for chrysotile and amphibole:

Volume of sample examined,
Limit of detection (as defined in 6.2),
Number of fibres counted,
Mean fibre concentration,
95% confidence interval for mean fibre concentration,
Estimated mass concentration,
Dimensions of the longest fibre counted,
Dimensions of the shortest fibre counted.
The dimensions of the fibres counted were used to estimate the mass concentration of chrysotile and amphibole in each sample. The densities of chrysotile and amphibole used for these calculations were 2.55g/cm³ and 3.20g/cm³ respectively. On the basis of American and Canadian surveys (8,9) fibre concentrations of less than 1.5 million fibres per litre are considered to be low.

7. DESIGN OF THE SURVEY AND THE CHOICE OF SITES

The analysis of asbestos in drinking water is expensive and the amount of money available meant that only about 130-150 samples could be taken, depending on whether they were dirty or clean. (Dirty samples are more expensive to analyse than clean ones as they require additional treatment). Because it was necessary to take duplicate samples at each site (see section 6.1) only 65-75 sites could be investigated. The survey was therefore a limited one and its aim was to establish the range of levels in British drinking water. The information generated would be insufficient to make an estimate of population exposure.

It is convenient to divide the survey into two halves. In the first half which began in January 1980 36 sites were sampled. These included a variety of raw and treated water sources and a range of different distribution systems. After considering the results from these sites, DOE and WRC decided that the second part of the survey should try to determine whether and in what circumstances the use of asbestos in the distribution system contributes to the levels of asbestos in drinking water, also to discover whether naturally-occurring asbestos minerals present any pollution threat to local water supply. A further 36 sites were sampled. For the complete survey a total of 146 samples (including duplicates and controls) were sent to ORF for analysis.

8. THE SURVEY PART I

8.1. THE CHOICE OF SAMPLING SITES

When the survey began there was no reliable information on levels of asbestos in British drinking water. After consideration of the points outlined in section 3 it was decided that the first series of samples should include 'typical' water supply situations, where one would not expect asbestos levels to be different from the background, and also circumstances where the levels might be elevated. This part of the survey was necessarily exploratory and it was decided that the range of samples taken should include all the types listed in Table 8.1.
Table 8.1 Sample types to be included in Part I of the Survey

1. A range of water qualities (particularly of hardness)
   
   (a) Raw waters
   (b) Treated (finished) waters

2. (a) Surface sources including
   (i) upland catchments
   *(ii) lowland rivers (re-used and stored water)
   
   (b) Underground sources including
   *(i) boreholes close to asbestos waste tips

3. *Distribution systems containing asbestos materials e.g.
   (a) asbestos-cement pipe
   (b) asbestos-cement domestic storage tanks
   (c) reservoirs covered with asbestos-cement sheeting

   * situations where asbestos levels may be higher than the background.

8.2. LOCATION AND DESCRIPTION OF SAMPLING SITES

The locations of the sampling sites are given in Table 8.2 along with a brief description of the type of sites, the water quality and the nature of the distribution system. The samples were collected by local water authority personnel who were supplied with sample bottles prepared by the WRC. The pH of the waters sampled ranged from <5 to 9.3 and the total hardness from <5 mg/l⁻¹ to 400 mg/l⁻¹ (as CaCO₃).

8.3. RESULTS

The results for the first part of the survey are given in Appendix B. Table B.1 gives asbestos fibre concentrations for individual samples, the detection limit and the volume of sample examined. Table B.2 gives the mean of the two duplicate asbestos analyses at each site, unless the results are significantly different (see section 6.2.3). Table B.3 gives, for each sample the estimated mass concentration of chrysotile and amphibole, the number of fibres counted and the dimensions (length and diameter) of the longest and shortest fibres found. The dimensions of fibres longer than 5 μm are printed in italics.
8.4. ASBESTOS FIBRE CONCENTRATIONS

(Please refer to Tables 8.2, B.1 and B.2)

8.4.1. Sample Set 1

The chrysotile levels found in the samples were low. Although
the sample at Stowmarket had come through an A/C pipe the water is
not aggressive. No amphibole was detected.

8.4.2. Sample Set 2

With the exception of one sample the chrysotile levels were
low. The duplicate samples taken at Ufford are statistically
significantly different; one having a level of 2.1 MFL and the
other <0.41 MFL. This highlights the difficulty of characterising
levels of particulate matter using grab samples. Although the
water had passed through A/C pipe it was not aggressive. The
amphibole levels were very low.

8.4.3. Sample Set 3

Chrysotile levels in the treated water were low. The duplicate
samples taken at the field station are statistically significantly
different; one having a mean level of 2.1 MFL and the other a mean
level of 0.44 MFL. The water was slightly aggressive and passes
through 3 miles of A/C pipe. Nevertheless a level of 2.1 MFL is
not very remarkable. No amphibole fibres were found.

8.4.4. Sample Set 4

The levels of chrysotile and amphibole in these samples were
very low.

8.4.5. Sample Set 5

With the exception of one sample site, (see Table 8.2. (L6))
levels of both chrysotile and amphibole encountered in this system
were low. Statistically there is no difference between the levels
in the raw and treated water, in dip samples taken from an A/C tank
or in water collected from a kitchen tap fed by this A/C tank. The
last two samples were taken in an occupied flat, in a block of
municipal flats. The plumbing is conventional. A large roof tank
feeds the whole block, the supply to each flat being via copper
piping to an A/C domestic storage tank. These tanks measure 40" x
20" x 20" and are covered with a lid. This block is due for
demolition and an additional two dip samples were taken from an A/C
tank in a flat which had been unoccupied for more than 6 months.
No amphibole was found but the chrysotile levels are very high; one
sample with 57.7 MFL has the highest level found in the first half
<p>| Sample Set 1 | Anglian Water Authority (Stour Water Division) | G1 | Treated water, Bayham Pumping Station, Suffolk Kitchen tap, Stowmarket, Suffolk | Borehole source; pH 7.1 and total hardness 400 mg/l⁻¹ A/C(d)²: 350mm D(1) and 6 inch D (15) |
| Sample Set 2 | Anglian Water Authority (Stour Water Division) | H1 | Treated water, Buckleham Pumping Station, Suffolk Kitchen tap, Martlesham, Suffolk | River derived source; pH 7.6 and total hardness 300 mg/l⁻¹ A/C(d): 350mm D (1), 6 inch D (6) and 4 inch D(4) A/C(d): 12 inch D(6) and 4 inch (4) |
| Sample Set 3 | North West Water Authority (Northern Division) | J1 | Treated water, Scotforth filter house, Lancaster Tap at the University of Lancaster Biological field station, Bailrigg, Lancaster | Upland catchment source; pH 9.0 and total hardness 50 mg/l⁻¹ A/C(d): 2.5 miles of 24&quot; D (&gt;20), cast iron: 2.5 miles of 15&quot; D and A/C(3): 0.5 miles of 12&quot; D (&gt;15) |
| Sample Set 4 | North West Water Authority (Pennine Division) | K1 | Treated water, Castleshaw filter house, Saddleworth, Oldham Kitchen tap, Barlsey, Oldham | Upland catchment reservoir; pH 9.3 and total hardness 50 mg/l⁻¹ Cast Iron; 4 miles and A/C (d) less than 0.5 miles of 6&quot; and 4&quot; D (&gt;10) |
| Sample Set 5 | North West Water Authority (Pennine Division) | G1 | Treated water, Wicken Hall Treatment works Finished water, Wicken Hall treatment works Solver service reservoir A/C domestic storage tank in an occupied flat, Sholver Estate Kitchen tap supplied by A/C tank in L4 above A/C domestic storage tank in an unoccupied flat, Sholver | Upland catchment source; pH approx. 9.3 and total hardness &lt;40 mg/l⁻¹ Final water: from treatment works service reservoir Cast iron mains leads to the reservoir, which is covered Dip samples taken. Estate is mostly served by cast-iron mains Dip samples taken |
| Sample Set 6 | Strathclyde Regional Council (Ayr Division) | M1 | Raw water, Roseburn intake, Isle of Arran Service tank, Brodic, Isle of Arran Drinking water tap, Roseburn Farm Museum, Brodic, Arran Drinking water tap in public convenience, Brodic, Arran | Upland catchment source; pH approx. 5 and total hardness &lt;5 mg/l⁻¹ A/C: 171m of 6 inch D and 75m of 5 inch D (1958) A/C: 300m of 7 inch D and 60m of 6 inch D (1958) A/C: 695m of 6 inch D and cast iron: 30m of 2 inch D (1958) |
| Sample Set 7 | Strathclyde Regional Council (Pendrew Area) | N1 | Finished water, Craigenleeoch filters, Johnstone First kitchen tap, Johnstone Second kitchen tap, Johnstone | Upland catchment source; pH approx. 7 and total hardness 2C – 50 mg/l⁻¹ A/C(d): 100m of 4 inch D laid in 1970 A/C(d): 370m of 4 inch D laid in 1970 |</p>
<table>
<thead>
<tr>
<th>Table 8.2. Continued</th>
<th>Site Code</th>
<th>Site Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sample Set 8</strong></td>
<td>P1</td>
<td>Finished water, Fulwood treatment works, Somerset</td>
</tr>
<tr>
<td>Westex Water Authority</td>
<td>P2</td>
<td>Fulwood service reservoir, Somerset</td>
</tr>
<tr>
<td></td>
<td>P3</td>
<td>Kitchen tap, Taunton, Somerset</td>
</tr>
<tr>
<td><strong>Sample Set 9</strong></td>
<td>Q1</td>
<td>Inlet to Hilltop service reservoir, nr Huddersfield</td>
</tr>
<tr>
<td>Yorkshire Water Authority</td>
<td>Q2</td>
<td>Outlet to Hilltop service reservoir, nr Huddersfield</td>
</tr>
<tr>
<td>(South Western Division)</td>
<td></td>
<td>Upland catchment source: pH 8.4, total hardness 130 mg.l⁻¹</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reservoir is covered with a 30 yr old asbestos sheet</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Water which has passed through cast iron mains only</td>
</tr>
<tr>
<td><strong>Sample Set 10</strong></td>
<td>R1</td>
<td>Chlorinated and screened raw water, Bedford Waterworks</td>
</tr>
<tr>
<td>Anglian Water Authority</td>
<td>R2</td>
<td>Stored raw water, Bedford Waterworks</td>
</tr>
<tr>
<td>(Bedford water Division)</td>
<td>R3</td>
<td>Treated water, Bedford Waterworks</td>
</tr>
<tr>
<td><strong>Sample Set 11</strong></td>
<td>S1</td>
<td>Raw water, after storage (50 days) and rapid sand</td>
</tr>
<tr>
<td>Thames Water Authority</td>
<td>S2</td>
<td>filtration, Walton works</td>
</tr>
<tr>
<td>(Metropolitan Water Division)</td>
<td></td>
<td>Treated water, Walton works</td>
</tr>
<tr>
<td><strong>Sample Set 12</strong></td>
<td>T1</td>
<td>Water Supply Pumping Station,</td>
</tr>
<tr>
<td></td>
<td>T2</td>
<td>Northernmost observation borehole No.1 (5m below rest water level)</td>
</tr>
<tr>
<td></td>
<td>T3</td>
<td>Southernmost observation borehole No.2 (15m below rest water level)</td>
</tr>
<tr>
<td>Source</td>
<td>T4</td>
<td>Easternmost observation borehole No.3 (10m below rest water level)</td>
</tr>
</tbody>
</table>

**Notes**
1. Abbreviations used to describe A/C pipe: D = diameter, a figure in brackets denotes either the age of the pipe or the year in which it was laid e.g. (10) or (1962). Measurement units are those current when the pipe was laid.
2. A/C (d): water which has passed through bitumen dipped asbestos cement pipe.
3. A/C: water which has passed through grey asbestos-cement pipe.
of the survey. It seems that the moderately aggressive water had stood in the tank for more than 6 months. The duplicate samples taken here were significantly different. The first one contained 6.9 MFL and it is likely that when it was taken the contents of the tank were stirred up resulting in the second very high level of 57.7 MFL. This supposition is further supported by the fact that only 5% of the fibres in the first sample were >5 μm in length but 30% of the fibres in the second sample were >5 μm. It is reassuring that the levels in the tank in the occupied flat were so low.

The use of such tanks in municipal housing was quite common until the early 1970's when an increase in public awareness of the dangers of asbestos caused many local authorities to choose alternative material. The largest user of such tanks was the Greater London Council (17). However, the water in the London area is hard and it is unlikely that these tanks would be corroded. In addition much of the use has been for domestic hot-water tanks and not for mains storage tanks.

8.4.6. Sample Set 6

These samples were taken in a 24 year old A/C system which carried an extremely aggressive untreated water. Levels of amphibole found were very low. However, the levels of chrysotile, while not exceptional, appear to be somewhat higher than the levels in many samples taken in this part of the survey; the means of the duplicates for the Brodick service tank and the drinking water tap in Brodick being 1.08 MFL and 1.75 MFL respectively. However, statistically there is no significant difference between these levels and those of the raw water source. The duplicates taken at Rosaburn farm were significantly different from each other. One had a mean fibre concentration of 0.86 MFL and the other sample contained 4.2 MFL. This higher level could be as a result of corrosion of the A/C pipe or it could be due to contamination of the sample at some stage of analysis.

8.4.7. Sample Set 7

These samples were taken in a 12 year old A/C system which is carrying an aggressive water. The levels of chrysotile found were low and no amphibole fibres were found. There was no significant difference between asbestos levels in the source water and the tap water.

8.4.8. Sample Sets 8 and 9

Both these sets included samples taken from reservoirs covered with asbestos-cement sheeting. The analytical sensitivity of the duplicate samples taken at the inlet to Hilltop service reservoir was degraded because of the presence of fine inorganic particles.
and fragments of diatoms. However, the levels of chrysotile and amphibole found in all these samples were low and there is no evidence that A/C sheeting on reservoirs contributes to asbestos levels in drinking water.

8.4.9. Sample Sets 10 and 11

The samples in both these sets were taken from re-used river sources at different stages of treatment. No amphiboles were found in any of the samples. The mean concentrations of chrysotile in the duplicate samples of chlorinated and screened raw water at Bedford waterworks are 25.6 MFL and 7.12 MFL. However, the 95% confidence intervals are wide because the analytical sensitivity is poor due to the presence of large amounts of platey inorganic materials in these samples. This restricted the volume of sample which could be filtered. Levels found in the stored raw water are lower (2.68 MFL and 5.6 MFL) and the analytical sensitivity is better, although there are still amounts of platey inorganic minerals present. The chrysotile levels in the final water are very low.

The levels of chrysotile in Thames raw water after storage and rapid sand filtration are very low. However, one of the samples of the final water has a mean concentration of 11.2 MFL which is very high for a water which is ready for distribution. It is difficult to explain such a level in this type of sample.

8.4.10. Sample Set 12

These samples were taken from boreholes in the vicinity of a landfill in which it was thought there might be asbestos waste. A duplicate pair of samples were taken from a public supply borehole about 0.8 km from the landfill. Raw water from the borehole is pumped to a treatment works and the proportion of water from the sampled borehole in the final water leaving the treatment works is less than 20%. Other boreholes are sited closer to the landfill but these are observation boreholes for monitoring the aquifer and are not used for potable purposes.

The landfill is on clay above glacial sands and gravels which overlay a considerable thickness of Upper Chalk. The gravels are in hydraulic continuity with the Chalk. There is evidence of pollution of the aquifer by contamination which may be derived from leachates from domestic wastes. Hydrogeological investigation of the site suggests that the landfill is the probable source of the pollution and the presence of asbestos in the boreholes may confirm this. (The detailed report of the hydrogeological investigations is sub-judice and remains confidential). In this instance, movement of the pollution plume may be facilitated by the highly
fissured nature of chalk. Little is known about the movement of asbestos fibres through different media, although some work has begun at Cambridge University in conjunction with Thames Water Authority (61).

ORF had some difficulty in analysing these samples because of the presence of large amounts of non-asbestos, platey materials which degraded the analytical sensitivity. However, ORF concluded that samples from the northernmost and southernmost observation boreholes did contain significant amounts of chrysotile. Levels of amphibole were low or insignificant in all the samples. The chrysotile levels in the well source were low and these samples were relatively clean. The samples taken at the northernmost and easternmost observation boreholes contained sub-micron, spherical particles which gave EDXA spectra showing only iron. They also contained many fibre-like fragments of diatoms, often in bundles. Samples from the southernmost observation borehole contained large numbers (85-180 MFL) of non-asbestos fibres which yielded EDXA spectra showing silicon, aluminium and sometimes also iron and magnesium. All the samples contained platey materials and particles which yielded EDXA spectra showing only calcium.

8.5. MASS CONCENTRATION AND FIBRE DIMENSIONS

Although the mean concentration of asbestos fibres in many of these samples is up to 1 MFL, the fibres are very tiny and the mass concentration per litre is very low. The highest mass concentration of chrysotile (2.04 μg/l) was found in the sample taken from an A/C domestic storage tank (unoccupied flat). It is clear from these data that it is not possible to estimate mass concentration from numbers of fibres alone (and vice versa), as has sometimes been attempted elsewhere. Mass concentration can only be estimated when details of fibre dimensions are available. Fibre size distributions are generally considered to be more important than mass concentration in determining health effects of asbestos. Until this issue is resolved both fibre concentrations and mass concentrations should be reported.

Only 9 amphibole fibres were found in the 72 sample examined and all of these were <2 μm in length. The estimated mass concentrations were very low. Only 8 out of 72 samples contained chrysotile fibres greater than 2μm in length and only 5 out of 72 samples contained chrysotile fibres greater than 5μm. Four of this last group were samples associated with asbestos-cement products. The longest chrysotile fibres 17 μm and 35 μm were found in the samples taken from the A/C domestic storage tank in an unoccupied flat. In the second sample taken here 30% of the fibres were >5 μm in length. However, this was a rather untypical sample.
8.6. SUMMARY

The levels of amphibole asbestos found in these samples were considered to be very low. The levels of chrysotile were also low. Fifty-six of the samples taken were potable water and of these only 10 samples had chrysotile levels greater than 1 MPL and only 2 samples had levels greater than 3 MPL. With the exception of a rather anomalous result for a sample of Thames water taken at Walton treatment works (see section 8.4.9) all of the samples of finished waters at treatment works contained less than 1 MPL. Only two samples for potable consumption contained fibres >5 μm in length.

9. THE SURVEY, PART II: THE EFFECT OF NATURALLY-OCCURRING ASBESTIFORM MINERALS ON ASBESTOS LEVELS IN LOCAL WATER SUPPLY

There are no outcrops of asbestos minerals in Britain which are being commercially exploited at present although they may have been in the past. As mentioned in section 3.1 the DOE commissioned a report from the IGS on the occurrence of asbestiform minerals in Britain. It was concluded that these outcrops would not have a serious impact on public water supply (10). WRC has not seen this report but, as far as WRC could ascertain, there are only two outcrops with any commercial potential; one of these is at Lochnagar in Scotland and the other is in Snowdonia (11).

9.1. LOCHNAGAR, SCOTLAND

This outcrop was investigated by the WRC Scottish Office. The mineral, which is chrysotile serpentine, is not being worked. The outcrop runs from O.S. grid reference NO. 316898 to NO. 333940. A small stream, Girnock Burn, drains east to the River Muick at NO. 348919. This river crosses the Balmoral estate and supplies private cottages. It is probable that Balmoral itself is supplied from this source. There are no public supplies in the area and so it was decided not to sample here.

9.2. SNOWDONIA, NORTH WALES

This outcrop occurs on the eastern slope of Moel Yr Ogof (approximate grid reference O.S. sheet 115 559477). It is an amphibole and geologically occurs in thin basic tuff between two basalt flows (62). Run-off from the outcrop flows into Afon Dwyfor. The Cwmysttradllyn reservoir lies in the same catchment and this is the main supply for the Lleyn Peninsula. However, the run-off from Moel Yr Ogof enters the main river below the intake for water supply and therefore does not affect the quality of the supply. Consequently it was also decided not to sample here.
10. THE SURVEY, PART II: INVESTIGATION OF THE CONTRIBUTION OF ASBESTOS MATERIALS IN THE DISTRIBUTION SYSTEM TO ASBESTOS LEVELS IN DRINKING WATER

Four possible sources of asbestos in the distribution system were identified:

(a) A/C sheeting or roofing for service reservoirs,
(b) A/C pipe,
(c) A/C cisterns,
(d) Asbestos rope and graphite/asbestos rope (used to pack glands and joints in pipes, taps and valves).

Results for the first half of the survey showed that A/C sheeting for service reservoirs was unlikely to increase asbestos levels in water (see section 8.4.8) and it was decided that no further samples would be taken in such situations. For reasons explained later no further samples were taken from asbestos cisterns nor was there any investigation into whether asbestos rope or graphite/asbestos rope contributed to levels in tap-water (section 11). Thus the sampling effort for the second half of the survey was concentrated on A/C pipe.

10.1. FACTORS AFFECTING THE DESIGN OF A SAMPLING PROGRAMME FOR ASBESTOS CEMENT PIPE

10.1.1. Water Quality

The factors which affect the behaviour of A/C pipe under various water quality conditions are poorly understood. Asbestos fibres may be released from the pipe by mechanical or chemical means. Maintenance work in the distribution system, especially drilling and tapping, could result in the former type of release, whilst the latter occurs in response to water quality conditions.

Chemical attack on a pipe is controlled by the aggressivity of the water it carries. However, American research (63,64,65) suggests that consideration of some measure of aggressivity alone (such as Langelier Index (LI) or Aggressive Index (AI) - for explanation see Appendix C) is not sufficient to predict fibre release. Very aggressive waters (AI <10 or a negative LI) do not always attack the pipe in the manner expected. It is thought that the presence of divalent ions (such as iron, zinc and manganese) or organic matter may lead to the deposition of a protective coating on the interior of the pipe, preventing release of fibres.

A review of the literature within WRC suggested that the sampling for this limited survey should concentrate on soft waters over a range of pH.
10.1.2. Distribution system characteristics

Once the water quality parameters had been defined several WRC databases were consulted to see which Regional Water Authorities (RWA) possessed such water and used A/C pipe. Statistics on the use of A/C pressure pipes for drinking water are poor but estimates of the number of kilometres in service have been made (68). On the basis of this information, a preliminary approach was made to a number of water undertakings.

(a) Pipe linings

Many water authorities were unable to say whether or not the pipes they used were bitumen-dipped (dipped) or not (grey). A visit was made to TAC Construction Materials Ltd (September 1981) who are the main manufacturers of A/C pipe in Britain. From their sales records they know that 65% of pipes sold for water mains are dipped. Therefore it was assumed that all the pipes sampled were bitumen-dipped, unless there was evidence to the contrary. Not much is known about how long such a lining would last but it is thought that in an aggressive water it would have deteriorated after 7-8 years.¹

(b) Length and Age of Pipe

Once a suitable water supply had been located there was very little choice over the length and age of pipe which could be sampled. Where there was a choice, it was felt that provided the pipes were more than 10 years old it would be preferable to sample as long a system as possible. This decision was partly influenced by the fact that most of the A/C pipes which WRC had sampled previously were between 1 and 7 years old.

10.2. SAMPLING DESIGN

Because of the high cost of individual asbestos analyses much thought was given as to how a pipe system should be sampled and which water quality parameters should be measured. If fibre release occurs in a pipe system, it is likely to be an intermittent process, depending on the chemical condition of the water and the physical conditions in the pipe such as presence of coatings and flow regime. Thus the sampling scheme must be able to indicate whether there is a possibility of occasional, elevated asbestos levels in the pipe.

¹ The bitumen lining had disappeared on all 20-30 year old pipes examined as part of a project on the deterioration of rubber glands by the Materials Group (WRC, Engineering Centre Swindon).
It was felt that variation in levels might be similar to the intermittent variation in iron and manganese levels in systems which have dirty water problems. Therefore the sampling scheme (Figure 10.1) included, for each system, one sample from an end hydrant which had been flushed hard to scour the main. In addition, a tap sample was taken from a house close to the hydrant before and after flushing. Samples taken from a hydrant (either at a dead end or elsewhere) and samples taken from a tap after flushing a hydrant are thus 'non-representative' of the system. However, they give an indication of a hypothetical 'worst case', and if the levels in these samples are low there is unlikely to be any problem in the system under normal conditions.

Advice on the chemistry of corrosion (16,70) suggested that the following determinands should be measured:—

- pH
- Temperature
- Conductivity
- Dissolved oxygen
- Hardness (by calculation)
- Alkalinity
- Silica
- Total phosphate
- Orthophosphate
- Total organic carbon

- Sulphate
- Chloride
- Iron
- Manganese
- Aluminium
- Zinc
- Copper
- Calcium
- Magnesium
- Sodium

Visits were then made to several RWA’s. Figure 10.1 was used as a basis for discussion with distribution engineers before deciding on the most suitable locations in their distribution systems for sampling. Seven A/C systems were finally chosen. One in North West Water Authority (NWWA), two in Yorkshire Water Authority (YWA) and four in Welsh Water Authority (WWA).

10.3. FIELDWORK

One of the systems in YWA turned out to be unsuitable in the field and the samples were rejected; therefore six systems were investigated. The lengths of A/C pipe sampled ranged from 375 m to 10.5 km and the ages of the pipe varied from 7-33 years. All the systems carried soft water the pH ranging from 5.4-9.2 and the initial Al from 7.3 to 11.7. (The LI ranged from -0.2 to -4.6)

Within in each system all the samples were collected within 24 hours. At every sample point temperature, conductivity and dissolved oxygen were measured on site and the following samples were collected.

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1 This term will be used frequently in the discussion of the results. Samples of water going into distribution or tap-water samples are termed 'potable' or 'representative' samples.
Figure 10.1 Layout of an A/C system suitable for sampling

System A: Proposed Sampling Points

A1 Raw water at source
A2 Raw water at treatment works
A3 Treated water at treatment works
A4 Water in 6" A/C main (at a hydrant)
A5 Mains water (i.e. flushed sample) at kitchen tap
A6 Sample from the end of the system after flushing the hydrant hard
A7 Mains water as in A5 (above) after flushing and hydrant

NOTES ON SAMPLING

1. It is important that there has been no recent maintenance work (such as drilling, tapping and scraping, etc) on these pipes.

2. Samples A1 and A2 will be taken only if water is carried from source to treatment works via an A/C pipe.

3. At each tap the length and diameter of the service pipe between the main (or in the case of A1, the final water) and the tap is ascertained. The tap is turned on until the flow is about 4 litres per minute. Ten pipe-volumes of water are flushed through before sampling commences.

4. The hydrant box cover is removed and the hydrant valve cracked open gently. An aluminium standpipe is attached and the hydrant is opened further. Water is allowed to run to waste for at least three minutes before samples are taken. This hydrant should not be flushed hard as the purpose of this sample is to determine the water quality in the main and not to disturb any deposits in the pipe.

5. The procedure is as in 4 above. However this time, once the standpipe is attached the valve is cracked fully open and flushed hard for 1 - 5 minutes. Samples are then taken from the standpipe without reducing the flow of water.
(a) For asbestos analysis – four 1 litre samples (ORF required 2 litres of each sample (see section 6.1) and WRC sent a 'blind' replicate of each sample for analysis).

(b) For water quality characterisation – 1.2 litres unacidified, 1 litre acidified with nitric acid and 500 ml acidified with hydrochloric acid.

Each distribution system is described in detail in Appendix D.

10.4. RESULTS

The results for the second part of the survey are given in Appendix E. Table E.1 gives the results of water quality analyses for each sample, with the exception of determinands measured on site. These data are given in Table E.2 with the length of A/C in each system and the Langelier Index of the water as it entered the system. Table E.3 gives asbestos fibre concentrations for individual samples, the detection limit and the volume of sample examined. Table E.4 gives the mean of the two duplicate asbestos analyses at each site, unless the results are significantly different (see section 6.2.3). Table E.5 gives, for each sample the estimated mass concentration of chrysotile and amphibole, the number of fibres counted and the dimensions (length and diameter) of the longest and shortest fibres found.

10.5. DISCUSSION

The reader will find it helpful to refer to the diagrams of each system which are given in Appendix D. Figures D1-D6.

10.5.1. Oldham (NWWA)

The length of A/C pipe in the system is 713 m and it carries a soft, but not very corrosive, upland water. The pipe is less than 10 years old. Before passing through the A/C pipe, the water is carried by a concrete-lined iron pipe. The samples taken at hydrants (B2, B4) and also from the tap after flushing the hydrant (B5) were orange in colour, and the ORF reported that the analytical sensitivity for these samples was degraded owing to the level of total inorganic solids present. The water quality analyses showed that levels of iron and manganese were higher in these samples than in the others, and so too were levels of calcium and hardness suggesting that flushing had disturbed the pipe coating. The levels of chrysotile and amphibole in water going into distribution are low (B1). The samples taken at the tap before flushing (B3) also have low chrysotile levels. However, one of these samples contained a number of amphibole fibres (0.94 MFL).
All the other fibre counts for amphibole are very low. The only sample in which a significant number of chrysotile fibres were found was taken from the hydrant at the dead end. These fibres ranged in length from $<1\ \mu m$ to $22\ \mu m$ with a median length of about $4\ \mu m$.

All the samples contained diatoms and all except the first tap-water samples contained material which yielded EDXA spectra showing peaks for silicon and aluminium with varying amounts of iron. These materials were present as platey particles and also as fibre-like particles (aspect ratios $>3:1$, see section 6.1).

Thus for this system the levels of asbestos in the potable water samples are low and statistically there is no significant difference between the water going into distribution and the tap water. The mean concentrations of asbestos in the hydrant (non-representative) samples were higher than elsewhere in the system.

10.5.2. Halifax (YWA)

This system consisted of ductile iron pipes and more than 1 km of 30 year old A/C pipe. The water (upland catchment source), has a negative Langelier Index and is moderately aggressive. In the field the samples taken at the first three sites appeared clean. However, those taken from the end hydrant and from the tap after flushing the hydrant were very dirty.

An examination of the water quality data shows that the samples taken at the first hydrant (C2) had slightly higher levels of iron, manganese, zinc, aluminium and total organic carbon, than the water leaving Ogden treatment works (C1). The levels of these parameters at the kitchen tap (C3) were very similar to that at Ogden. However, the levels of these parameters in the sample taken from the end hydrant (C4) were much higher. This sample also had much higher levels of copper, calcium, magnesium, total hardness silica and total phosphate. This is because, as intended, the flushing disturbed deposits on the pipe surface. When the tap was sampled again (C5) the levels of some parameters had returned to their previous level (C3) but levels of iron, manganese, zinc, aluminium, total hardness and total organic carbon were still slightly elevated.

The levels of asbestos (chrysotile and amphibole) in the water leaving Ogden (C1) and in the tap-water (C3) were very low and not significantly different. The end hydrant and final tap water samples contained obvious sediment which degraded the sensitivity of the analysis. The levels of chrysotile were higher at the hydrants than elsewhere in the system. The levels of amphibole were highest at the end hydrant and in the tap-water after the pipe deposits had been disturbed. All of these fibres were very small, only one fibre, an amphibole, being greater than $2\ \mu m$ in length.
10.5.3. Dolwyddelan (WWA)

The water in this system is more aggressive than that of the previous systems and A/C is the only material used. In the field all the samples collected appeared to be very clean, even flushed samples taken from the end-hydrant (D6). Examination of the water quality data shows that there is very little change in the levels of determinands between potable samples and hydrant samples. There is a slight difference in the level of some parameters between raw and treated waters, simply as a result of the addition of chemicals to prevent corrosion. It is interesting to note that the levels of iron and manganese in the system are very low but do increase about ten times in the flushed hydrant sample (D6). Even so the level is still low (iron = 0.51 mg.l⁻¹ and manganese = 0.140 mg.l⁻¹) and the change would not be apparent to the naked eye. WWA scientists suggested that these pipes (especially those carrying raw water) could be coated with humic material. Such deposits may prevent fibre release (see section 10.1.1). It was thought that flushing the hydrant hard would disturb this but the colour of the samples (at D5, D6 and D7) and the levels of TOC, did not indicate that this had happened.

ORF reported that the analytical sensitivity for all these samples was good. The levels of chrysotile were very low in the samples of raw water (D1, D2), water going into distribution (D3), hydrant samples from the 4" A/C main (D4) and in the water at the kitchen tap (D5). However, the levels in the samples taken at the end hydrant (D6) were very high as were the levels at the tap after flushing the end hydrant (D7). The chrysotile fibres in these last four samples ranged from 1 μm to 27 μm in length, 70-80% were <5 μm and the median length was 2 μm.

The distribution of amphibole fibres in the samples is rather different. The levels in the lake samples are very low. Looking at Table E.4, the levels at sites D2-D5 appear to be much higher than the levels in the source water, but this difference is not significant. There are significantly more amphibole than chrysotile fibres in these samples, but the levels are still low. As with chrysotile, flushing the end hydrant increased the levels significantly at the tap. One very large amphibole fibre in a final tap-water sample accounted for 92% of the estimated mass concentration of amphibole in that sample.

ORF reported that all the samples contained platey minerals, some of which conformed to the definition of fibre but could be discriminated from amphibole by their SAED patterns. Diatoms were also present. Many of the samples contained fibres which gave SAED patterns visually comparable to amphibole and EDXRA spectra with peaks corresponding to silicon, iron, aluminium, calcium and low
levels of magnesium. Any fibres in which the peak area for aluminium was greater than that for magnesium have not been included in the reported amphibole values (3). Some of the samples also contained non-asbestos fibres giving EDXA spectra showing only titanium (probably rutile). The highest levels of these fibres were found in the raw water samples taken at the filter beds.

10.5.4. Rhdymain (WWA)

Again the only material used in the distribution system is A/C pipe which is about 30 years old. The spring source is an aggressive groundwater (LI = -2.8) with a low organic content. The only treatment is chlorination and there is no hydrant on the 1275 m pipe owing to its small diameter. Thus only 2 sites were sampled; the borehole itself and a kitchen tap in Rhdymain village. There was no appreciable difference in the water quality at the two sites.

The levels of chrysotile and amphibole at both sites were very low. All four samples contained platey materials, and diatoms, including fibre-like fragments of diatoms. ORF commented that the tap-water samples were very clean and contained sub-micron spherical particles which yielded EDXA spectra showing mainly iron.

10.5.5. Friog (WWA)

The village is supplied by an upland catchment. The water is soft with a Langelier Index of -2.6. The conductivity of the water is low and in general the water quality varies little throughout the system. The distribution mains consist entirely of A/C. As observed previously the levels of iron and manganese are higher in the non-representative samples than in the potable samples. Again this is not apparent to the naked eye and all the samples appeared clean.

The levels of chrysotile in the raw water (E3) and in the 3" hydrant samples (E4) were low. The levels at the kitchen tap (E6) were also low. The levels of amphiboles in these samples were extremely low. In one of the raw water samples only one fibre was counted but it was long (>8 \(\mu m\)). There was no significant difference between asbestos levels at the source and at the tap.

Chrysotile levels in the samples taken at the 6" hydrant (E5) were >2 MPL and the levels at the end hydrant (E7) and in the tap sampled after the end hydrant (E8) was flushed were much higher. These samples all contained some fibres longer than 5 \(\mu m\); one sample at E8 having fibres ranging from 1-12 \(\mu m\).

With the exception of the hydrant on the 3" main, the amphibole levels at all the non-representative sites were elevated but less so than the chrysotile levels.
All the samples in this series contained fibres (probably rutile) which gave EDXMA spectra showing only titanium. The water at the source and at the 3" hydrant contained many fibre-like fragments of diatoms and the samples at the 6" hydrant contained fibres which gave EDXMA spectra showing peaks for iron only.

10.5.6. Corris/Dovey Bridge (WWA)

The supply to Corris and Dovey Bridge is derived from surface water and spring sources impounded in a reservoir above Corris. The water is very aggressive and as it goes into distribution has a Langelier Index of -4.6. The distribution mains consist entirely of A/C pipe only, the length from the source to Dovey Bridge being more than 10 km.

The water quality does not vary much throughout the system. However, levels of iron, manganese and total hardness are higher in the hydrant samples (sites F6, F8, and F10) and at the tap after flushing the hydrant (F7 and F11). In the field, all the samples appeared clean. Levels of both chrysotile and amphibole were low in the reservoir samples (F1), the raw water at the filter beds (F2), the water going into distribution (F3), the water at the first hydrant (F4) and the tap water in Corris (F5). The samples taken after flushing the hydrant (F6) had higher levels of chrysotile (mean concentration of 8.3 MFL at the hydrant and 2.7 MFL at the tap). These samples also contained fibres up to 10 μm in length. However, these levels are not significantly different from the levels in the treated water at the filter beds. The levels of amphibole remained low.

Two samples were taken at a hydrant 6.3 km from Corris. The levels of iron, manganese, chrysotile and amphibole in these samples were very low. The final six samples were taken at Dovey Bridge. The hydrant which was flushed at Dovey Bridge (F10) is not at a dead end. (See Appendix D. Figure D.6). Water from here continues to Marchlyn Reservoir. Occasionally water may be pumped in the reverse direction from Marchlyn Reservoir to Dovey Bridge. This length of pipe therefore experiences flow reversals. The results for these samples were surprising because they did not conform to the pattern of previous systems. Levels of both chrysotile and amphibole at the tap in Dovey Bridge were much higher than those in any other potable water sample in the whole survey. The levels were significantly higher (p = 0.001) than the levels in the water going into distribution in Corris. There are three factors which may account for this. Firstly, the water is the most aggressive sampled. Secondly, the length of A/C pipe is the longest sampled and thirdly the pipe experiences variable flows in either direction. These samples contained chrysotile and amphibole fibres greater than 5 μm in length.
The flushed samples from the hydrant at Dovey Bridge also contained higher levels of chrysotile. The analytical sensitivity of these samples was degraded because of the level of inorganic solids present (the higher values for total hardness, iron and manganese suggest that flushing has scoured the internal pipe-surface). The levels of amphibole were high in one sample and low in the other. The samples taken from the tap after flushing the hydrant were rather inconsistent for chrysotile. The analytical sensitivity for these samples was good. The levels of amphibole were low. However, the chrysotile levels were significantly different from each other (one having a mean concentration of 7.1 MFL and the other only 0.29 MFL). In the latter sample only 2 fibres were counted but the amphibole fibre was >7 μm long and the chrysotile fibre was >11 μm long. ORF remarked on the unusual length of the chrysotile fibres in the samples taken at Dovey Bridge. Very thin fibres up to 30 μm long were found. All the samples contained non-asbestos fibres (probably rutile) which gave EDXA spectra showing peaks for titanium only. They also contained diatoms and platey materials which frequently demonstrated a fibre-like morphology.

10.5.7. Control Samples

Two control samples were included amongst the 74 samples sent to ORF during the second part of the survey. Sample bottles were prepared as described in section 6.1, they were then filled with double-distilled water, resealed with parafilm and despatched to ORF with other samples. The results are given in Appendix E, (Tables E3 and E5). ORF remarked that these samples were very clean containing only low levels of platey particles and some diatoms.

10.5.8. Comparison of chrysotile and amphibole levels

The general points made in section 8.5 concerning mass concentration and fibre dimensions also apply to this discussion.

Many more amphibole fibres were counted in the second half of the survey than in the first. Seven of the 72 samples contained amphibole fibres greater than 5 μm in length; two of these were potable water samples. In general the mean concentrations of amphibole in water were similar to those of chrysotile with the exception of the hydrant samples. Here the levels of chrysotile were much higher than elsewhere in the system while the levels of amphibole were only slightly elevated.

Sixteen of the 72 samples contained chrysotile fibres >5 μm long, but only one of these (at Dovey Bridge) was from a potable water sample, the rest were non-representative.
Generally the amphibole fibres were much thicker than the chrysotile fibres. Amphibole is also more dense so that even where fibre counts were higher for chrysotile the estimated mass concentrations of amphibole were greater.

10.5.9. Water quality and the release of fibres from A/C pipe

It is beyond the scope of this report to investigate the relationship between water quality and asbestos fibre concentration in any great detail. American work (63,64,65) suggests that there may be a quantitative relationship between certain water quality parameters and asbestos fibre concentrations in water passing through A/C pipe. When the second half of the survey was designed, it was decided that a variety of water quality parameters should be measured. It was accepted that it would not be possible to analyse these data fully for this report but since there is no reliable information on asbestos in U.K drinking water and the analysis is so expensive, it was felt that it would be short-sighted not to characterise the water quality of the samples.

10.5.10. Summary

Twenty-six of the samples (13 sites) were of potable water (i.e. they were not raw water nor hydrant samples). With the exception of those taken at Dovey Bridge, none contained concentrations of chrysotile or of amphibole in excess of 1 MFL.

In every system except the Halifax system, the highest concentrations of chrysotile and amphibole were found at the dead end. Samples taken at hydrants always had higher concentrations of chrysotile than non-hydrant samples, even when the hydrant had not been flushed but opened gently to sample water in the main without disturbing pipe deposits. The situation with amphibole was less clear-cut. There were significantly more amphibole than chrysotile fibres in most of the Dolwyddelan samples. However, these levels were low. Amphibole was found much more frequently in the second part of the survey than in the first.

11. FURTHER DISCUSSION

11.1. LEVELS OF ASBESTOS IN POTABLE WATER

Taking the two parts of the survey together, we have a total of 82 samples representative of potable water. Of these only 12 contained chrysotile fibre concentrations greater than 1 MFL. Ten of these 12 samples were taken during the first part of the survey at nine different sites. At only one site did both first and second samples have levels greater than 1 MFL; at the other eight sites the second sample contained less than 1 MFL. For five of these eight sites the duplicate samples were significantly different from each other. This highlights the difficulty of measuring particulate matter by means of grab samples. The possibility must also be considered that contamination may have
occurred in some cases. Only two samples contained more than 3 MFL chrysotile. One of these was taken from a tap on the Isle of Arran and contained 4.3 MFL. Its duplicate contained 0.86 MFL and the two samples were significantly different. The other sample was of finished water at Walton Works (Thames Water). This sample contained 11.2 MFL and its duplicate 0.85 MFL. These results are significantly different and are very difficult to explain.

Only one sample in the first part of the survey contained more than 1 MFL amphibole asbestos (1.4 MFL). This was taken at the inlet to Hilltop Reservoir (Yorkshire Water). However, the confidence limits on this result are wide (Table B1).

In the samples taken from asbestos-cement systems all of the 26 potable water samples contained less than 1 MFL chrysotile asbestos, with the exception of the two tap water samples from Dovey Bridge, which contained 7.1 and 15.3 MFL. Four samples contained more than 1 MFL amphibole asbestos. Two of these were taken in Halifax: one of the final water samples at Ogden treatment works (C1) contained 1.4 MFL and the tap water sample (C3) contained 1.3 MFL. However, the mean concentrations at each of these sites were 0.4 and 0.7 MFL respectively. The two samples taken at the kitchen tap in Dovey Bridge contained 7.1 and 13.8 MFL.

The Dovey Bridge samples were taken after water from Corris had passed through 10.5 km of A/C pipe and the levels of asbestos in the tap water were significantly different from those at the works. As discussed in section 10.5.6 the water in the pipe was extremely aggressive, a very long length of pipe was involved and the section of pipe experienced flow reversals. Because the levels found were so much higher than elsewhere it may be worthwhile having a look at the levels here again.

From the results of the complete survey only four potable water samples (three sites) contained more than 3 MFL asbestos (amphibole and chrysotile). The levels in UK drinking water are therefore low and certainly much lower than levels in countries where asbestos is mined (8,9).

11.2. LEVELS OF ASBESTOS IN DISTURBED WATER FROM A/C PIPES

The concentrations of asbestos in samples taken from hydrants or after flushing were generally higher than in the samples representative of water as normally drawn for drinking. These higher concentrations could be caused by the accumulation of fibres released from the pipes, from low levels of fibre in the original water supply or from drilling and tapping operations on the pipe system. The relative contributions of these sources is not known. Although these disturbed samples are not representative of water that would normally be consumed they give an indication of the levels of asbestos concentration that could, under unfavourable conditions, occur in a household supply.
11.3. DIFFERENCE BETWEEN LEVELS IN RAW AND TREATED WATERS

Excluding re-used river sources, the highest mean concentration of chrysotile asbestos found in a raw water was 1.4 MFL and the highest concentration of amphibole found was 0.95 MFL. The levels in raw water from re-used river sources were higher. Chlorinated and screened raw water samples from the Bedford Ouse contained 7-25 MFL of chrysotile but no amphibole.

The stored water at these works contained 2-5.6 MFL chrysotile and no amphibole, but the treated water going into distribution contained less than 0.33 MFL. Levels of both chrysotile and amphibole in raw water at Walton treatment works (Thames Water) were very low after filtration. As discussed previously, the two samples of finished water taken at Walton were contradictory. No amphiboles were detected in either sample, but one contained 0.85 MFL chrysotile and the other 11.2 MFL.

American research has shown that conventional filtration removes asbestos (71,72,73). However because in the present survey only a small number of raw water samples were taken and with the exception of the Ouse samples, they contained low levels of asbestos, it is not possible to confirm this effect with regard to asbestos levels in the UK.

11.4. DIMENSIONS OF FIBRES

Detailed comments about the distribution of fibre dimensions are given in sections 8.5 and 10.5.8. A comparison of the two parts of the survey (Table B3 and E5) shows that all samples containing chrysotile asbestos fibres longer than 5 \( \mu \text{m} \) are associated with asbestos-cement materials. However, only one of these samples was a potable water sample. This was at the Biological Field Station near Lancaster (North West Water). The rest were in non-representative samples. The longest chrysotile fibres were found in the second part of the survey and exceptionally long fibres were found in the Dolwyddelan system.

Most amphibole fibres were found in the second part of the survey. All of those found in the first half were less than 2 \( \mu \text{m} \) in length. Seven samples in the second part contained amphibole fibres greater than 5 \( \mu \text{m} \) in length, but these were all non-representative samples. Over 95% of fibres found in representative samples were less than 2 \( \mu \text{m} \) in length.

11.5. SUBJECTS FOR FURTHER INVESTIGATION

As the survey described was a limited one, there are several areas where some further investigation may be useful.
11.5.1. A/C storage tanks

The extent of the use of these tanks for potable purposes is not known. Samples were taken from two tanks and these results are described in section 8.4.5. The data from these samples are insufficient to allow an assessment of whether these tanks contribute to levels in drinking water.

11.5.2. Asbestos and graphite/asbestos rope

Asbestos is used for gaskets and packing in water pumps and asbestos rope is used to pack pipe joints and tap-glands. Further information is required about the extent of these practices, which are thought to be widespread. This limited survey could not investigate whether these materials contribute to levels in water.

11.5.3. Asbestos waste disposal to land

Documentation of asbestos waste disposal in the past was not very good. A large effort would be required to identify locations for sampling. Only one situation was investigated in the survey. Thus, the survey cannot indicate the extent to which past disposal practices have contributed to levels in drinking water, particularly ground water.

11.6. COMPARISON WITH OTHER SURVEYS

The results of this survey are comparable with the results of the American and Canadian surveys (8,9) described previously, particularly since many of the analyses have been performed by the same laboratory (ORF). Another survey has recently been completed by Meyer in West Germany (74). The investigation of the occurrence of asbestos fibres in German water also included an evaluation of the results in terms of health effects. The results are not directly comparable with the British results because the method of analysis used was different. However, the paper describes the procedure in detail. Meyer measured only fibres down to 1 \( \mu m \) in length (using magnifications of between 5,000x and 10,000x). Thus, as he admits, a number of fibres in the 1-5 \( \mu m \) range would not have been observed because their diameters were too small. In his paper he only reports the number of fibres found which were >5 \( \mu m \) in length. (Most of the fibres found in the WRC samples were <2 \( \mu m \) in length and the magnifications used were 20,000x). Meyer's reason for reporting only these fibres is that present health research does not suggest that fibres <5 \( \mu m \) are carcinogenic. Meyer reports the results of asbestos levels before and after passage through A/C pipe. Examination of pipe sections showed, as in the EPA studies (63,64,65), that waters with a negative Langenier Index attack the cement matrix but this process is sometimes prevented by the presence of coatings such as iron-oxide. However as only mean concentrations of fibres >5 \( \mu m \) are given, a comparison with the UK data is very difficult.
11.7. STANDARDS FOR ASBESTOS LEVELS IN DRINKING WATER

The World Health Organisation, the EEC and the EPA believe that at present there is insufficient information on which to recommend an action level for asbestos in water (75). The US National Academy of Sciences are evaluating all available data on ingested asbestos and their report is expected in January 1983. EPA reviewed all their work on asbestos ingestion in October 1982. Based on this, and on economic considerations and treatment technology, an advance notice of proposed rulemaking concerning asbestos in drinking water will be issued in 1983.

12. CONCLUSIONS

1. The analytical procedure developed by the Ontario Research Foundation is a reproducible method for enumerating and characterising asbestos in water. This method is shortly to be adopted as the recommended procedure by the US Environmental Protection Agency.

2. The levels of amphibole asbestos in UK drinking water are low, nearly all the samples contained less than one million fibres per litre (MFL).

3. The levels of chrysotile found in UK drinking water are also low. Only 12 samples out of 82 potable water samples contained more than 1 MFL and only four samples (at three sites) contained more than 3 MFL.

4. The survey results suggest that most drinking waters in the UK contain asbestos fibres in a range from 'not detectable' to 1.5 MFL and that more than 95% of these fibres are < 2 μm in length.

5. With the exception of re-used river waters, the levels of chrysotile and amphibole asbestos in raw waters was within the range described above. The levels of chrysotile and amphibole in finished water going into distribution were also within the range (with the exception of one sample taken at Walton Treatment Works which is discussed). Because most of the raw water samples contained only low levels of asbestos, it was not possible to comment on the effect of conventional treatment methods on asbestos levels in water.

6. Levels of amphibole asbestos in samples taken from asbestos cement piping systems were higher than elsewhere but still low. Levels of chrysotile in potable water samples taken from these systems were all <1.5 MFL with the exception of three sites.
Most of the non-representative samples (i.e. hydrant samples, flushed hydrant samples, tap samples taken after flushing the hydrant and dip samples taken from an A/C tank) all contained much higher levels (up to 58 MFL) than the potable water samples. Intermittent exposure to such levels could therefore occur. These levels probably represent the upper end of such intermittent exposure for consumers of water in the UK.

7. A number of outcrops of asbestos minerals in Britain were investigated. Their locations did not affect any public water supplies and, because of the cost of the asbestos analysis and the limited nature of the survey, they were not sampled.

8. The results of this survey are comparable with more extensive work in the US and Canada. The results of the British survey compare very favourably with levels in N. America.
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