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ASBESTOS/CEMENT PIPE CORROSION
PART 1 - HISTORICAL, TECHNOLOGICAL, ECONOMIC AND STATISTICAL BACKGROUND

B. NEBESAR AND G.W. RILEY

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by

B. Nebesar* and G.W. Riley**

ABSTRACT

A critical evaluation of the causes of asbestos/cement pipe corrosion and possible prevention of release of asbestos fibres was required on the basis of information contained in several published reports on asbestos fibres in drinking water systems. The question, whether asbestos ingested with drinking water is harmful, has not yet been resolved. This report presents background information on the history of asbestos/cement and asbestos/cement pipe; on technology comprising raw materials, the asbestos/cement matrix, manufacturing processes, specifications, properties and uses of asbestos/cement pipe; and on related economic and statistical data. The aim is to help bridge the differences among readers from various fields and provide useful information on which to base decisions. References from North American, European and Australian sources are cited.

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*Research Scientist, and **Manager, Mineral Processing Laboratory, Mineral Sciences Laboratories, CANMET, Energy, Mines and Resources Canada, Ottawa, K1A 0G1.

CORROSION DES TUYAUX EN AMIANTE-CIMENT
PREMIÈRE PARTIE
DOCUMENTATION DES ÉLÉMENTS HISTORIQUES, TECHNOLOGIQUES, ÉCONOMIQUES ET STATISTIQUES

par

B. Nebesar* et G.W. Riley**

RÉSUMÉ

À cause de l'information présentée dans plusieurs rapports concernant les fibres d'amiante présentes dans l'eau potable, on a reconnu la nécessité d'une évaluation critique portant sur les causes de la corrosion de tuyaux en amiante-ciment et les possibilités d'empêcher l'échappement des fibres. On n'a pas encore répondu à la question du danger de l'ingestion de l'amiante trouvé dans l'eau potable. Le présent rapport offre des données de base sur l'histoire du mélange amiante-ciment et des tuyaux en amiante-ciment; sur la technologie qui comprend les matières brutes, la matrice amiante-ciment, les procédés de fabrication, spécifications, propriétés et emplois des tuyaux en amiante-ciment; et sur les données statistiques et économiques connexes. Le rapport vise donc à établir des rapports entre lecteurs de différentes disciplines et à fournir de l'information utile qui pourra aider à prendre des décisions. On cite des références dont les sources sont nord-américaines, européennes et australiennes.

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*Chercheur scientifique, et **gestionnaire, Laboratoire du traitement des minéraux, Laboratoires des sciences minéraux, CANMET, Énergie, Mines et Ressources Canada, Ottawa, K1A 0G1.

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1. INTRODUCTION

There is no life without water. Indeed, the World Health Organization (WHO) estimates that some 25 x 10^6 people die every year from diseases caused by unclean or inadequate water or by lack of sanitation. Provision of safe drinking water and simple sanitation, combined with basic information about hygiene, are perhaps more important for the health of the world's people than food or any amount of sophisticated medical treatment.

Therefore, the United Nations Organization carefully planned and launched in November 1980 the "International Drinking Water Supply and Sanitation Decade" (IDWSSD) (1,2). By 1990, "safe water for everyone" should no longer be a dream. To realize this goal in this decade for an additional 2 x 10^9 people is an enormous technological, financial, and organizational task that is impossible to achieve.

Asbestos/cement (A/C) high- and low-pressure pipe has been used extensively throughout the world for water distribution, sewage, drainage, and irrigation systems since its invention at the beginning of the century. It was estimated that about 2.5 x 10^6 km of A/C pipe had been installed worldwide by 1972. This pipe has proven to be one of the most reliable, economical, technologically suitable and therefore, until recently, generally accepted products.

Recently, however, because of the health implications of asbestos, primarily in respiratory passages, A/C pipe has come under close scrutiny with other asbestos-containing products. The perception of risk from asbestos in air has been extended to include potential risk from drinking water if delivered through A/C pipes. While the medical community, environmentalists, and other investigators continue their aetiological investigations, the technical aspects - particularly the corrosion of A/C pipe - are also being re-evaluated.

Until recently the mechanism of corrosion, or degradation of A/C pipe and the ensuing possible release of asbestos fibres, was not entirely understood. Moreover, the occasional corrosion in the enormously expanded systems which now serve millions of people was considered more a technical and economic rather than a health problem. The new implications for health of the possible release of asbestos into water led recently to much work on understanding and preventing this occurrence.

Part 1 presents a short historical background and provides a description of A/C technology in general and of A/C pipe in particular. Economic and statistical data supply the necessary perspective.

Part 2 reviews the problems of A/C pipe corrosion and recent improvements in its control.

2. HISTORICAL BACKGROUND

2.1 ASBESTOS/CEMENT

Asbestos/clay was the first composite used by man. It appeared about 4000 years ago (3,4). However, asbestos/cement (A/C) was the first industrially exploited fibre-cement (Section 3.2).

At the end of the last century, asbestos was becoming abundantly available from Russia and Quebec. Inventors everywhere tried to use it in new technological applications, but without much success. Although A/C had been known since 1879*, it was not until 1901 that it was used by Ludwig Hatschek to start a flourishing building-products industry in his native Austria-Hungary. He invented and patented in Austria (1901) the machinery and process based on the papermaking machine, and developed the necessary technical knowledge for the large-scale manufacture and commercialization of a new building component - A/C roofing sheet.

Klos (5,6) and Huenerberg and Tessendorff (7) described this technological development in detail. They also cited many attempts to circumvent the original patent.

Hatschek worked originally with asbestos on textile machinery. Later he produced various asbestos products, eventually mixing asbestos with

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* Probably a U.S.A. patent

paper pulp, asphalt or pitch as binders, and zinc or magnesium oxides. He finally succeeded in forming roofing sheets from this mixture on a paper pulp machine. These sheets were impregnated with the respective chlorides or water glass after formation. They still can be seen today on some roofs in Austria.

The breakthrough came when Hatschek began to use portland cement and asbestos in water. The first trials were unsuccessful because the thick mass required by the conventional cement technology soon clogged the machine, necessitating frequent stopping and cleaning. The decision to use a thin slurry of asbestos and cement in a large excess of water eventually solved the problem.

When Hatschek died in 1914, a variety of A/C products were being manufactured on the basis of his wet process in several countries (Section 3.3). Then, as today, these products were mainly used in the building industry. Cossette and Delvaux (8) and Badollet (9) give detailed lists of more than 3000 A/C building products and other technical applications of asbestos minerals. Moreover, the manufacture of seamless pipes based on similar principles was invented in 1913 replacing the square-form gravity and non-pressure pipes which had been laboriously made by hand from A/C sheets.

2.2 ASBESTOS/CEMENT PIPE

The manufacture of A/C pipe closely followed the mechanization of A/C sheet forms but inherent technical problems were much more difficult. Klos (5), Huenerberg and Tessendorff, (7), and Carrière (10), reported that in about 1912, Mazza and Mattei in Italy, had succeeded in modifying the original Hatschek-type machine to permit the manufacture of seamless A/C pipe. In 1913, in Genoa, the Public Corporation "Eternit" obtained a patent for the machine-system "Mazza" and started producing these pipes in their Casale-Monferrato factory near Milan.

Also in 1913, the first A/C water distribution systems were laid in Casale. The canalization systems followed soon after. In 1923, A/C pipes were used in Genoa to flush the streets with sea water which would have corroded the metallic piping. The name "Eternit" - clearly linking the A/C with eternal indestructibility - reveals perhaps what was thought of this material at the time.

By 1921, A/C pipe was well accepted in Europe. The first water distribution system was built in Germany in 1930, and in The Netherlands in 1931. In the United Kingdom, production had started in 1928. By 1935, the length of A/C pipe laid in Italy was already about 10 000 km. In 1929, Johns-Manville Corporation, USA, acquired rights to its manufacture and sale.

Although several other types of pipe-manufacturing machines were invented, the "Mazza" system is still predominantly used throughout the world. The rapid and universal acceptance of A/C piping indicates the extent to which it has succeeded in economically solving the pressing needs of water distribution and sanitation.

3. TECHNOLOGY OF ASBESTOS/CEMENT PIPE

3.1 RAW MATERIALS

3.1.1 Asbestos

Asbestos is a generic name, generally given to a group of five fibrous silicate minerals: chrysotile, crocidolite, amosite*, anthophyllite and tremolite. Their fibres can easily be separated so that their diameters measure a few nanometres. Chrysotile is the asbestiform variety of serpentine; the others are the asbestiform variety of amphibole minerals.

In Table 3-1, Rosato (11) gives the chemical compositions of the five asbestos minerals and in Table 3-2, Eick (12) summarizes their main properties.

The chrysotile fibres are hollow, generally soft, and very flexible. They have the highest content of magnesium oxide and water. The amphiboles are not hollow and are generally harsher and considered less flexible. An electron micro-

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*Asbestos Mines of South Africa - mineralogically mostly cummingtonite-grunerite

Table 3-1 - Chemical composition of various types of asbestos* (11)

	Chrysotile %	Crocidolite %	Amosite %	Antho-phyllite, %	Tremolite %
SiO_2	37-44	49-53	49-53	56-58	51-62
MgO	39-44	0-3	1-7	28-34	0-30
FeO	0.0-6.0	13-20	34-44	3-12	1.5-5.0
Fe_2O_3	0.1-5.0	17-20	-	-	-
Al_2O_3	0.2-1.5	-	2-9	0.5-1.5	1.0-4.0
H_2O	12.0-15.0	2.5-4.5	2-5	1.0-6.0	0.5
CaO	Tr-5.0	-	-	-	0-18
Na_2O	-	4.0 to 8.5	-	-	0 to 9
$CaO+Na_2O$	-	-	0.5 to 2.5	-	-

*Encyclopedia of Chemical Technology, Vol. 2, New York and London, Interscience Publisher (1948).

graph from Rutstein (13) illustrates the difference in appearance (Fig. 3-1). Only a very small quantity of serpentine and amphibole minerals under particular geological circumstances occurs as the asbestiform variety of the mineral. The asbestiform varieties occur in veins or veinlets within rock containing or composed of the common (non-asbestiform) variety of the same mineral (14). The soft, silky fibres of asbestos are so flexible they can be spun into threads from which cloth can be woven. Asbestos has even been named "the silk of the mineral kingdom" (15). The varieties of asbestos produced commercially for A/C pipe are chrysotile, crocidolite (blue asbestos), and amosite. Chrysotile makes up 90% of the world production of asbestos of which about 70% is used for A/C products including pipe.

Regarding A/C pipe, the following more general references on asbestos are particularly useful: 5, 7-9, 11, 16-25.

For the manufacture of A/C products, the dust content, filtration behaviour, surface area and fibre diameter of asbestos fibre are particularly important. In Table 3-3 from Huenerberg and Tessendorff (7), the exceptional characteristics of the chrysotile are compared with several natural and artificial fibres.

Asbestos fibres are particularly suited to cement products because of their resistance to strongly alkaline conditions. Also, their high strength and flexibility allow them to withstand

Table 3-2 - Properties of different types of asbestos (12)

Name	Chrysotile	Crocidolite	Amosite	Tremolite	Anthophyllite	Actinolite
Crystal system	Monoclinic	Monoclinic	Rhombic	Monoclinic	Rhombic	Monoclinic
Mohr hardness	3.0-4.0	5.5-6.0	5.5-6.0	5.5-6.0	5.5	6.0
Specific gravity, g/cm^3	2.3-2.5	3.4	3.0-3.3	2.9-3.1	2.9-3.2	3.0-3.2
Resistance to acids	Very good	Good	Good	Good	Good	Very good
Resistance to alkalis	Very good	Good	Moderate	Good	Good	Moderate
Heat resistance	Good, brittle at high temperature	Good	Good, brittle at higher temperature	Good, brittle at higher temperature	Very good	-
Melting point, °C	1550	1250	1450	1350	1490	1390
Breaking strength, kg/cm^2	5600-10 000	6000-22 000	1000-6300	75-560	100-400	50-300

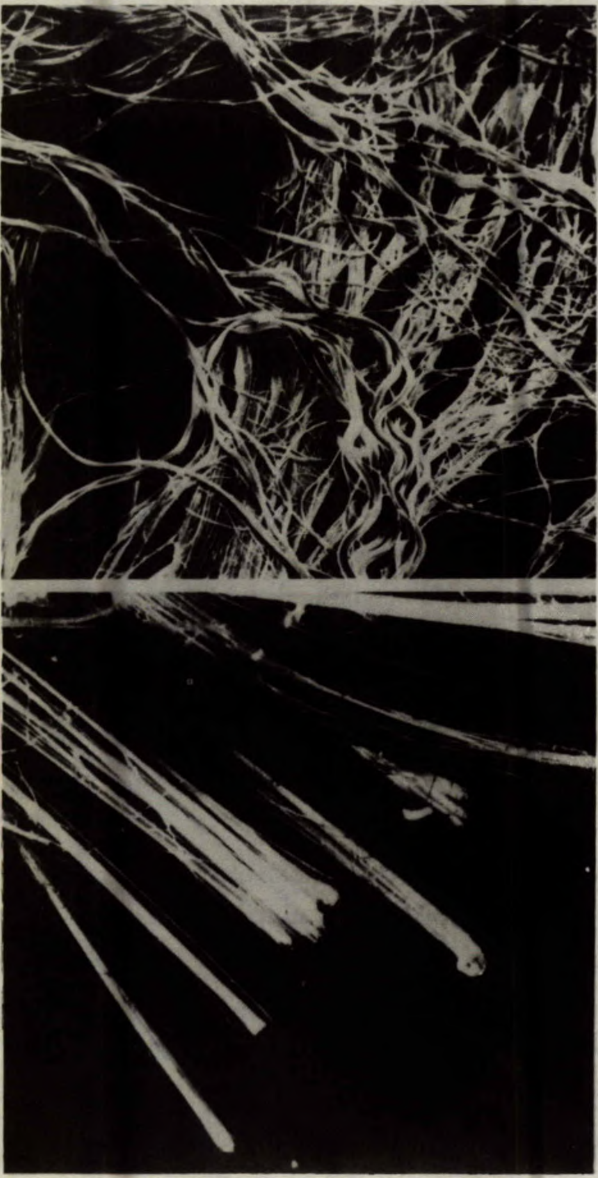


Fig. 3-1 - Difference between chrysotile and crocidolite (13):
The top photo shows the sinuous, curly fibres of chrysotile, or 'white asbestos', from near Globe, Ariz. Many of the fibres are thinner than 0.0001 cm. The bottom photo shows the needle-like fibres of crocidolite, or 'blue' asbestos, from Cape Province, South Africa. The fibres are about the same thickness as chrysotile fibres, but are short and straight. (U.S.G.S. photos).

the severe milling and fiberizing processing conditions required to prepare the fibres for use in A/C manufacturing.

In the western world asbestos fibres are classified commercially mainly according to the Canadian chrysotile asbestos classification system. However, special classifications for South African crocidolite and South African amosite exist.

Table 3-3 - Properties of various fibres (7)

Fibre type	Diameter mm	No. fibres per 1 mm	Fibre surface cm^2/g
Nylon	0.0075	132	3 100
Acetate	-	-	3 800
Cotton	0.01	100	7 200
Silk	-	-	7 600
Wool	0.02 to 0.0275	36 to 50	9 600
Viscose	-	-	9 800
Chrysotile	0.000018 to 0.000029	34 000 to 56 000	130 000 to 220 000
Human hair	0.0395	25	-
Ramie	0.0246	40	-
Glass	0.0065	153	-
Slag wool	0.00355 to 0.0071	141 to 282	-

Table 3-4 - Canadian chrysotile asbestos classification (8)*

Class	Standard designation of grade	Description
CRUDE ASBESTOS		
Group No. 1	Crude No. 1	- Consists basically of crude 3/4-in. staple and longer.
Group No. 2	Crude No. 2	- Consists basically of crude 3/8-in. staple up to 3/4 in.
	Crude run-of-mine	- Consists basically of unsorted crudes.
	Crudes sundry	- Consists of crudes other than specified above.

MILLED ASBESTOS

Class	Standard designation of grade	Guaranteed minimum shipping test (oz) 2 Mesh	4 Mesh	10 Mesh	Pan
Group No. 3	3F	10.5	3.9	1.3	0.3
	3K	7.0	7.0	1.5	0.5
	3R	4.0	7.0	4.0	1.0
	3T	2.0	8.0	4.0	2.0
	3Z	1.0	9.0	4.0	2.0
Group No. 4	4A	0.0	8.0	6.0	2.0
	4D	0.0	7.0	6.0	3.0
	4H	0.0	5.0	8.0	3.0
	4J	0.0	5.0	7.0	4.0
	4K	0.0	4.0	9.0	3.0
	4M	0.0	4.0	8.0	4.0
	4R	0.0	3.0	9.0	4.0
	4T	0.0	2.0	10.0	4.0
	4Z	0.0	1.5	9.5	5.0
Group No. 5	4D	0.0	0.5	10.5	5.0
	5K	0.0	0.0	12.0	4.0
	5M	0.0	0.0	11.0	5.0
	5R	0.0	0.0	10.0	6.0
Group No. 6	6D	0.0	0.0	7.0	9.0
Group No. 7	7D	0.0	0.0	5.0	11.0
	7F	0.0	0.0	4.0	12.0
	7H	0.0	0.0	3.0	13.0
	7K	0.0	0.0	2.0	14.0
	7M	0.0	0.0	1.0	15.0
	7R	0.0	0.0	0.0	16.0
	7T	0.0	0.0	0.0	16.0
	7W	0.0	0.0	0.0	16.0
Group No. 8	8S	Under 50 lb/ft^3 loose measure			
	8T	Under 75 lb/ft^3 loose measure			
Group No. 9	9T	Over 75 lb/ft^3 loose measure			

*A hard-converted metric standard has been approved at the sub-committee level but not yet accepted for general use.

In addition to the Quebec standard test, which is a special sieving test on a 454-g sample, a number of other testing and evaluation methods were developed. Cossette and Delvaux describe them in detail (8). The Canadian classification is reproduced in Table 3-4.

A typical A/C grade would be a 4T equivalent fibre with a minimum of -75 µm (-200 mesh) fraction and dust. Also, several other requirements must be satisfied (9). Particularly important is a high filtration rate.

A mixture of various grades and types of fibre typically made up of 80% chrysotile fibre, the remainder consisting of either crocidolite or amosite or both, to help improve filtration characteristics is used in manufacturing A/C pipe.

3.1.2 Cement

The fast growth of the A/C industry depended not only on asbestos but also on the fact that cement is, according to Hannant, a worldwide, easily and inexpensively available construction material (19).

Understanding the behaviour of cement is a prerequisite to understanding the corrosion of cement-containing matrices.

Like asbestos, cement is a generic name, given to complex hydraulic binders, which are a mixture of various oxides and compounds, setting and hardening without disintegration even in water. Helmuth et al. described the characteristics and technology of cement (26).

In the rotary kiln, used for sintering, the reactions of calcium oxide with acidic components give various cement clinkers, depending on the mix of raw materials and carefully controlled sintering process. Grinding, mixing and adding a proportion of gypsum - for controlling the setting - complete the manufacturing.

In the cement chemist's notation, the most common constituents are abbreviated as follows:

$CaO = C$
$SiO_2 = S$
$Al_2O_3 = A$
$Fe_2O_3 = F$
$MgO = M$
$SO_3 = \overline{S}$
$Na_2O = N$
$K_2O = K$
$CO_2 = \overline{C}$
$H_2O = H$

The most important constituents of cement are calcium, silicon, aluminum, and iron (III) oxides. Their relationships are schematically depicted in the triangular phase diagram from Franquin in Fig. 3-2 where the alumina is combined with iron oxide for two-dimensional representation (27).

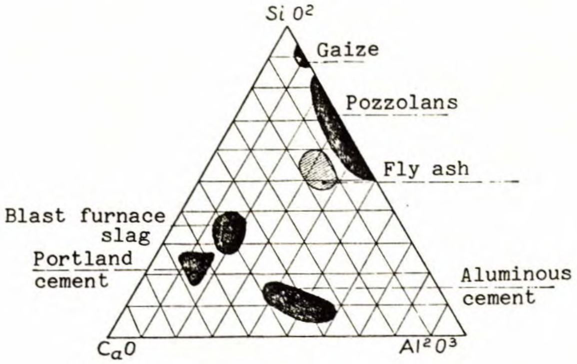


Fig. 3-2 - Triangular phase diagram of the composition of cements, slags and pozzolans (27)

The diagram gives the general composition of various classes of cements or additions to cement which are all used for A/C production.

The main components of portland cement, by far the most used, are:

Name of impure form	Cement chemists' notation	Chemical name
Alite	C_3S	Tricalcium silicate
Belite	C_2S	Dicalcium silicate
C_3A	C_3A	Tricalcium aluminate
Ferrite	~ C_4AF	Tetracalcium aluminoferrite
Anhydrite	$C\overline{S}$	Calcium sulphate

The first two constitute about 75% of the cement.

In the aluminous cements, the main component is calcium aluminate (CA).

In supersulphated cements, granulated blast furnace slag constitutes about 75%; the rest is calcium sulphate with some portland cement or lime.

Silica replaces up to 40% of cement in some formulations (Morbelli or hydrothermal process).

3.1.3 Water

Water is the reacting and transporting medium in the production of A/C pipe. Two of its parameters are important: hardness and pH.

If water is too soft, i.e., contains too little calcium and therefore an "aggressive" carbon dioxide, the corrosion will start even before production is finished. Calcium components from the cement matrix will be leached out. As make-up water, Klos specifies a medium-to-hard water, containing about 100 mg CaO/L (5).

Similarly, if water has a low pH, acids will be present which will dissolve the alkaline components of the cement stone.

Finally, water should not contain organic matter or more than 2% total dissolved solids as this would interfere with the reactions in cement.

3.2 ASBESTOS/CEMENT MATRIX

The A/C matrix is an artificial cement stone, reinforced with asbestos fibres. Both components synergistically contribute their properties to form a new material with enhanced characteristics. During the production of A/C pipe, there are three distinct stages of the matrix, each one decisively affecting the corrosion resistance of the product.

3.2.1 Asbestos/Cement Aqueous Slurry

Asbestos has an exceptional affinity to and carrying capacity for cement even in a slurry containing more than 90% water as required in the wet process. The dry phase contains from 15-20% asbestos, often of mixed varieties, and 80-85% cement. Up to 40% cement can be substituted with fine silica flour in an autoclave-curing (also hydrothermal or Morbelli) process (Section 3.3.1).

An important requirement for slurry is its ability to filter. As chrysotile filters less readily, up to 25% of the asbestos content is substituted with an amphibole variety - mostly amosite since crocidolite was banned.

3.2.2 Dewatered Asbestos/Cement

During the process, water is removed from the slurry until the A/C contains only about 20%. In spite of this, the buoyancy of asbestos, carrying high proportions of cement, continues. The fibres remain homogeneously distributed and bonded within the matrix. Water/cement ratio is now ≤ 0.3 and setting and hydration of the A/C matrix starts. The addition of amphiboles to the matrix also imparts greater density and better wet-handling capabilities to the set, but not yet hardened, pipe.

3.2.3 Hydrated Asbestos/Cement

Asbestos is not affected by water. Thus, only reactions of cement must be considered. There are three possible types of hydration of the manufactured pipe:

- Water-curing (normal) by immersion in water for 28 d;
- Steam-curing (at atmospheric pressure - not often used);
- Autoclave-curing, mainly used in North America and requiring silica addition.

Both main processes differ substantially in technology, in the resulting components of the A/C matrix, and possibly in the corrosion resistance of the pipe.

Cement constituents are unstable in the presence of water, but react with it to form stable hydration products. Thus, the main five components are transformed under water-curing conditions as follows (20):

C_3S, C_2S $\longrightarrow$ hydrated calcium silicate (tobermorite) gels, CSH-I and free lime, $Ca(OH)_2$

$C_3A + Ca(OH)_2 \longrightarrow$ hydrated tetracalcium aluminate $4\,CaO.Al_2O_3.12\,H_2O$

$C_4AF \longrightarrow$ mixed crystals of hydrated aluminoferrite $(Al_2O_3,\ Fe_2O_3).4\,CaO.12\,H_2O$

$C\bar{S}$ + aluminate $\longrightarrow$ hydrated calcium sulphoaluminate (ettringite) $3\,CaO.Al_2O_3.3\,CaSO_4.32\,H_2O$ also called: cement bacillus; Chandlot-Michaelis salt

ettringite $\xrightarrow[\text{few hours}]{\text{transformed}}$ hydrated calcium monosulphoaluminate $3\,CaO.Al_2O_3.CaSO_4.12\,H_2O$

In the autoclave-curing process, the added silica reacts with the liberated lime to form additional tobermorite. There is hardly any free lime. Moreover, according to Marks and Hutchcroft, both portions of the tobermorite formed are microcrystalline and therefore more chemically resistant (28). The results in Table 3-5 show the low lime content as well as the increased sulphate resistance.

Table 3-5 - Free-lime content and sulphate resistance of normal and autoclave-cured cements (28)

Type of cure	Silica/cement	Cement type	Free-lime (%)	Sulphate resistance: expansion (%)*
Autoclave, 125 psi	0.6/1.0	I	0.4	0.03
16 h		V	0.5	0.03
Normal underwater	0.0/1.0	I	15.5	0.16
28 d		V	13.7	0.11

*U.S. Bureau of Reclamation sulphate resistance test; measures expansion after 28 cycles.

The nature of the hydration products from the two other phases, C_3A and C_4AF, formed under hydrothermal conditions, is still unclear according to Crennan et al. (29). It is believed that C_3A hydrates into C_3AH_6, having small cubic-form crystals. Ferrite might form solid solutions of lime, alumina, silica and iron.

In the special high alumina cements, discussed by Crennan et al., some additional hydration reactions take place (29):

CA	normal cure	hydrated metastable hexagonal form
	hydrothermal cure	stable cubic form of C_3AH_6 (assumed) and hydrated alumina

Calcium hydroxide is absent in the hydration products of these cements.

Hydration products of the supersulphated cements are mainly calcium sulphoaluminate and calcium silicate hydrate. Calcium hydroxide is absent as well.

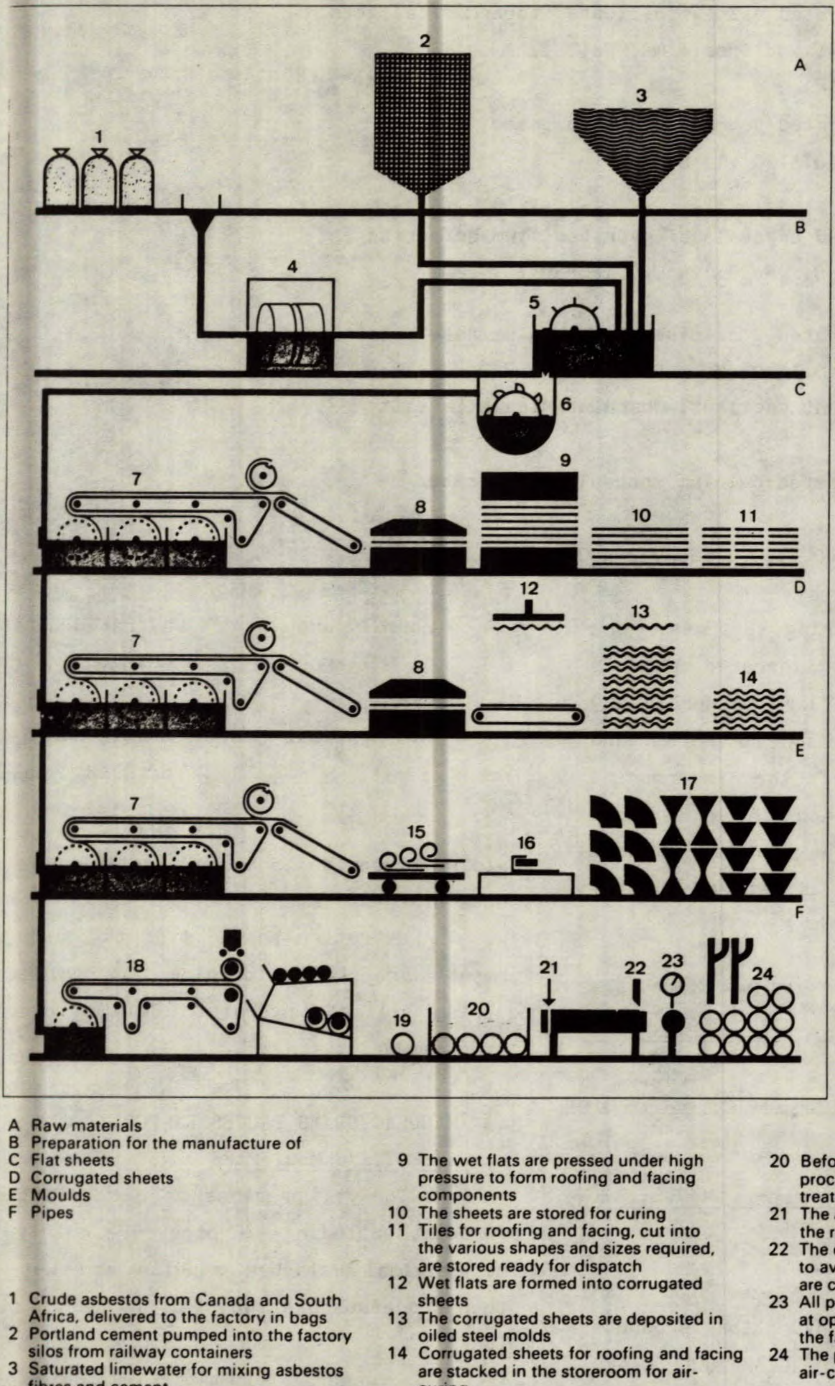
3.3 MANUFACTURING PROCESSES FOR ASBESTOS/CEMENT PIPE

Today's processes for manufacturing A/C products, including A/C pipe, are mainly based on the original Hatschek machine and wet process. Other processes are the semi-dry, dry, and extrusion.

A general schematic of the variants of the wet process, with a brief explanation of the main operations after Shepherd (30) and Bradfield (18), are presented in Fig. 3-3.

3.3.1 Mazza-Mattei Process

The schematic diagram for the Mazza pipe machine is shown in Fig. 3-4, after Huenerberg and Tessendorff (7). A close-up photograph of the pipe mandrels is shown in Fig. 3-5.



30
Schematic representation of the manufacture of asbestos-cement products.

A Raw materials
B Preparation for the manufacture of
C Flat sheets
D Corrugated sheets
E Moulds
F Pipes

1 Crude asbestos from Canada and South Africa, delivered to the factory in bags
2 Portland cement pumped into the factory silos from railway containers
3 Saturated limewater for mixing asbestos fibres and cement
4 In the kollergang the asbestos fibres are finely opened
5 The asbestos fibres and cement are mixed with ample water in the beater to form a homogeneous slurry
6 From the stirring tank, where the asbestos cement slurry is kept in continuous motion, the mixture is fed into the filter boxes of the machines which produce sheets or pipes
7 Rollers form the asbestos cement web into sheets 3 to 20 mm thick
8 The wet flats are cut into the required shapes on the cutting table
9 The wet flats are pressed under high pressure to form roofing and facing components
10 The sheets are stored for curing
11 Tiles for roofing and facing, cut into the various shapes and sizes required, are stored ready for dispatch
12 Wet flats are formed into corrugated sheets
13 The corrugated sheets are deposited in oiled steel molds
14 Corrugated sheets for roofing and facing are stacked in the storeroom for air-curing
15 The still unhardened flats are brought to the molding shop
16 By using different dies, articles of all shapes and sizes are produced
17 Flower boxes, plant pots, ventilation shafts and all the other various articles molded from asbestos cement are air-cured prior to delivery
18 A felt conveyor deposits layer after layer of the thin asbestos cement web on the steel mandrel, until the wall of the pipe reaches the desired thickness
19 The steel core can be removed only a few hours after manufacture
20 Before being subjected to final processing, asbestos cement pipes are treated with water in large tanks
21 The asbestos cement pipe is cut to the required length
22 The ends of the pipes are calibrated to avoid unnecessary work when they are coupled up during laying
23 All pressure pipes are carefully tested at operating pressure before leaving the factory
24 The pipes are stored in the open for air-curing

Fig. 3-3 - Schematic representation of the manufacture of asbestos/cement products (30)

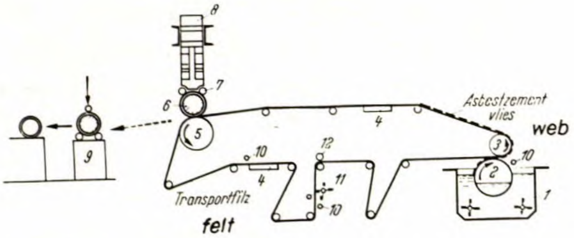


Fig. 3-4 - Schematic of Mazza pipe machine (7): 1 Slurry tank: 2 Screen cylinder; 3 Rubber roll; 4 Filter box; 5 Breast roll; 6 Mandrel; 7 Pressure rollers; 8 Pressure assembly; 9 Calender; 10 Spray pipe; 11 Felt beaters; 12 Felt-pressing rollers

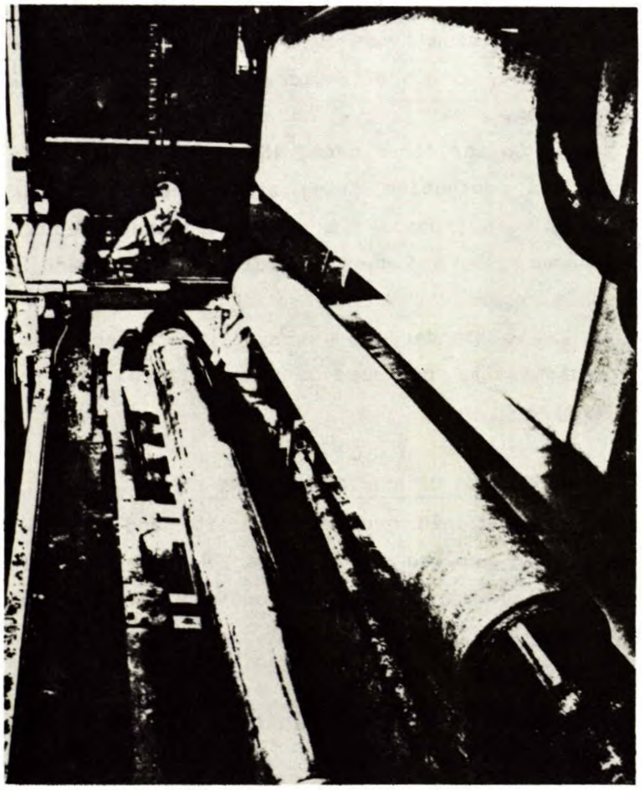


Fig. 3-5 - An asbestos/cement pressure pipe leaving the production machine (30)

There are three principal technical patents (all to Mazza) which eventually permitted the high-volume production of A/C pipe (5).

- Exchangeable mandrels for insertion into side ways swingable assembly, replacing the original Hatschek calender;
- Top pressure assembly rollers with a top felt, permitting compression of the A/C matrix and simultaneous removal of water;
- Automatically adjustable top pressure, permitting winding of thicker-wall pipe and preventing rotation of the mandrel under excessive pressure.

Following is a brief description of a typical machine. After suitable preparation, the A/C slurry enters the slurry tank (Fig. 3-4). Here, one or two rotating screen cylinders pick up the A/C matrix components from the slurry. An A/C web is formed and immediately transferred onto a continuously moving felt conveyor. The excess water is removed through filter boxes by vacuum. The substantially drier web is again transferred on a rotating and exchangeable steel mandrel, having a diameter of the desired pipe opening. Regulated pressure rollers exert additional pressure on the deposited layers and remove more water. The conveyor returns for another web.

Depending on the requirements, the thickness of one layer can be from a few tenths to ~1.5 mm, and that of the built-up pipe wall from ~8 to ~60 mm. The time required to produce one pipe on a typical machine is from 13 s to 6 min. The full metre-lengths of the pipe are standardized from 3 to 6 m and depend on the mandrel.

In the autoclave-curing (hydrothermal process), the set pipes are not kept for 28 d in water, as shown in the general scheme, but are hydrated within hours under high pressure and temperature in an autoclave, as shown in Fig. 3-6 from Rosato (11).

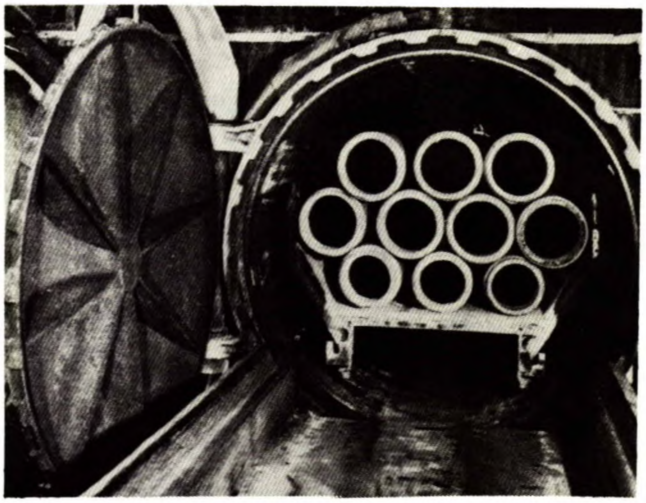


Fig. 3-6 - Asbestos/cement product cured in autoclave (11)

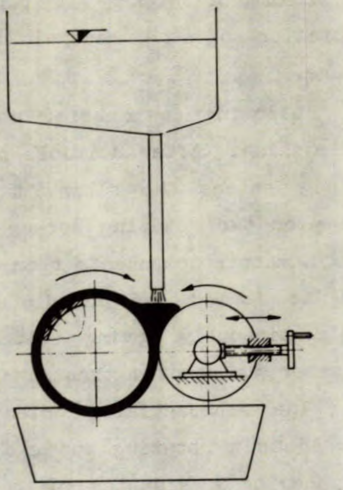


Fig. 3-7 - Cross-section of a Magnani pipe machine (5)

3.3.2 Magnani Process

The Magnani machine works with a semi-dry mixture. It is much less complicated, therefore more economical and used where a low production volume is acceptable. A schematic diagram of the principle from Klos (5) is presented in Fig. 3-7.

The mixture is distributed between the perforated, cloth-covered and slowly rotating mandrel and the form roller. Their distance can be gradually adjusted while water is removed by vacuum through the mandrel's centre and the pipe wall is formed. Calendering and removal of the cloth complete the operation.

3.3.3 Dalmine Process

In the Dalmine process several parallel narrow (~1250 mm) wet mechanical machines operate simultaneously (11). The pipe is built from the stock being placed on the same tubular mandrel in a spiral form. Each successive layer overlaps the previous one. The mandrel is positioned at an angle to the axis of the machines, it moves across them in operation, and is removable after calendering the pipe to the desired thickness. The complex process permits manufacturing of long pipe regardless of machine width.

3.4 SPECIFICATIONS FOR ASBESTOS/CEMENT PIPE

Dimensions and critical properties for pipes are standardized on organizational, national, and international levels. Among the best known are the joint standard ASTM 296-78 and C 500-79a of the American Society for Testing and Materials (ASTM) with American Water Works Association (AWWA) (31,32), the German standard Deutsche Industrie Normen (DIN) 19800 [reproduced in (7)] and the respective standard of the International Organization for Standardization (ISO).

From the viewpoint of corrosion, the DIN standard does not include any explicit chemical test or directive, as does the ASTM standard, for the free calcium hydroxide (maximum 1%) and the measurement, with applications, of the aggressiveness index.

On the other hand, ASTM does not specify corrosion protection films which are listed in DIN and most probably in other European national standards. Both issues are discussed in Part 2 of this report.

No standard as yet specifies measurement of potentially released asbestos fibre due to corrosion.

3.5 PROPERTIES OF ASBESTOS/CEMENT PIPE

Bradfield quotes durability and noncombustibility as the most desirable properties of A/C. In addition, he points out the other roles for asbestos fibre in A/C (18):

- Reinforcement of cement
- Protection from fire
- Absorption of heat from friction
- Insulation from heat, cold and sound
- Insulation from condensation
- Protection from corrosion
- Improvement of properties with exposure

A comprehensive evaluation of A/C pipe recently listed its advantages as resulting from (20):

- Composition	- extreme dispersion of asbestos fibres, strongly bonded to cement; no electrochemical corrosion or oxidation;

- Fabrication process - strong compression of web layers into a homogeneous mass; hydration of cement under controlled conditions;
- Structure - extremely fine capillaries allowing no penetration of aggressive fluids;
- Internal compressed surface - little danger of cavitation, deposits, or incrustations;
- Ageing - mechanical properties, compactness, and chemical stability increase with time.

Under certain conditions, A/C pipe may corrode. Causes of and remedies for corrosion are addressed in Part 2.

3.6 USES OF ASBESTOS/CEMENT PIPE

The asbestos/cement pipe has been successfully used for varied purposes, often in aggressive media. Following are examples from Huenerberg and Tessendorff (7), Shepherd (30), Marks and Hutchcroft (28), Sorès and Little (33):

- Water distribution (pressure)
- Sewage disposal (gravity or pressure)
- Agriculture - irrigation, drainage, manure
- Industry - telephone ducts, electrical cable conduits, gas vents, air ducts, air vents, stacks, process and storm drains, refuse chutes, district and geothermal heat, acid and salt-laden mining waters.

4. ECONOMIC DATA FOR ASBESTOS/ CEMENT PIPE

Table 4-1 - Apparent per capita world consumption of asbestos

Region	Apparent consumption (34), %	Population* millions	Apparent consumption, t	Per capita consumptio kg
Canada	0.7	24.21	36 568	1.51
European Economic Community (10 countries)	12.6	271.39	658 227	2.43
Japan	5.6	117.65	292 545	2.49
USA	10.1	229.81	527 626	2.30
USSR	40.5	267.70	2 115 729	7.90
Others	30.5	3 597.24	1 593 327	0.44
World	100	4 508	5 224 022	1.16

*World statistics in brief, 7th ed. United Nations, New York, 1983.

Table 4-2 - Apparent 1981 consumption of asbestos for asbestos/cement pipe relative to other products, USA and the world

	USA (35)		World*
	tonnes	%	
Asbestos/cement pipe	160 000	40.0	70%**
Flooring products	100 200	25.0	10
Friction materials	49 120	12.0	7
Roofing products	28 070	7.0	
Packings & gaskets	12 030	3.0	3
Coatings & compounds	12 030	3.0	2
Insulation/thermal & electrical	8 000	2.0	
Asbestos/cement sheets	8 000	2.0	
Textiles	2 000	0.5	1
Plastics	2 000	0.5	
Paper	500	less than 0.1	5
Other	20 050	5.0	2
	401 000	100.0	100

* Energy, Mines and Resources Canada estimates excluding East European countries

**includes all A/C products

Table 4-3 - Proportion of 1981 world consumption of asbestos for asbestos/cement products*

Region	Proportion for asbestos/cement from total uses, %
USA	44
Europe**	63
Japan	72
Other***	90
World	70

* Energy, Mines and Resources Canada estimates

** Except UK and East European countries

***Mainly developing countries

Table 4-4 - Per capita processing of asbestos, 1978 (36)

Region	kg	lb
Quebec	6.8	15
U.S.A.	3.0	6.6
Europe	3.2	7
Japan	2.8	6.2

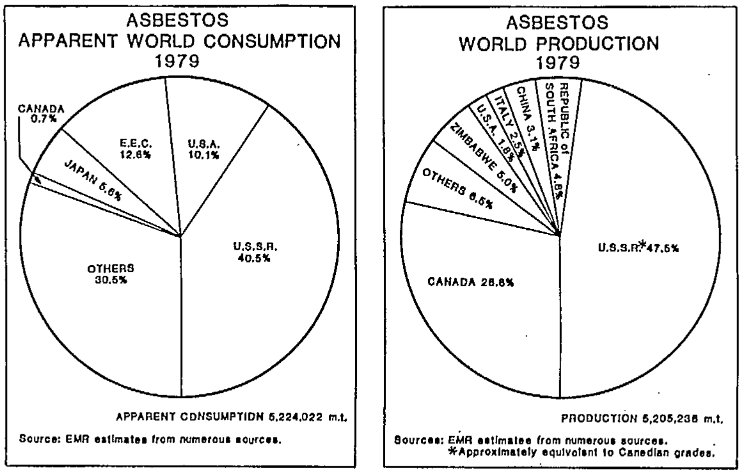


Fig. 4-1 - World production and consumption of asbestos, 1979 (34)

Table 4-5 - Typical dollar values per metric ton for Québec chrysotile, May 1979* (8)

Grade	Value	Grade	Value	Grade	Value
Crude No. 1	$3 000	4A	$1 002	6D	$332
Crude No. 2	2 295	4D	815	7D	216
3F	1 591	4T	719	7F	195
3K	1 353	5D	537	7K	136
3R	1 149	5K	537	7M	124
3T	1 043	5M	504	7R	114
3Z	1 023	5R	455	7T	112

*The cut-off ore value is $9.00/t for open pit and $20.00 for underground mines

Table 4-6 - Cost of asbestos relative to other fibres (37)

	Approximate Cost		Relative
Fibre type	$/tonne	$/m^3	cost
Chrysotile asbestos	130	330	1*
E-glass	1 200	3 100	9.4
AR-glass	2 800	7 600	23**
Fibrillated polypropylene	1 900	1 750	5.3
PRD-49	110 000	160 000	485
Steel	660	5 200	15.7
Stainless steel	3 300	26 000	79
Carbon	130 000	250 000	758

* Based on 1973 U.K. asbestos price of ~6 p/kg ($1.30/kg)

** 1983 relative cost: ~5

Table 4-7 - Relative energy cost of production of pipe materials (19)

Material	Cost factor per unit volume
Cement	1
Plastic	5
Steel	22

5. STATISTICAL DATA FOR ASBESTOS/ CEMENT PIPE

Table 5-1 - Regional breakdown of asbestos/cement pipes Canada 1976 (33)

Categories	East(1)	West(2)	Canada
Pressure pipes	11.1	88.9	100.0
Other pipes (mainly sewer)	64.0	36.0	100.0
Total	46.6	53.4	100.0

(1) Includes Quebec, Maritimes and part of Ontario.

(2) Includes Alberta, Saskatchewan, Manitoba and British Columbia.

Source: Sorès Inc., estimates

Table 5-2 - Breakdown of asbestos/cement pipes, according to end uses - Canada 1976 (33)

Categories	East	West	Canada
Pressure pipes	7.9	54.8	32.9
Other pipes (mainly sewer)	92.1	45.2	67.1
Total	100.0	100.0	100.0

Source: Sorès Inc., estimates

Table 5-3 - Market proportion of asbestos/cement pipe in Canada 1977 (33)

Categories	Proportion
Pressure pipe	18%
Sewer pipe	22%

Table 5-4 - Proportion of asbestos/cement pipe installed in U.S.A., 1980 (38)

Water main, 1.0 x 10^6 km		Sewer pipe, 7.4 x 10^5 km	
Cast iron	>75%	Vitrified clay	~66%
A/C pipe, 1.3 x 10^5 km	13	Reinforced concrete	6
Steel	6	A/C pipe, 4 x 10^4 km	5.4
Reinforced concrete	4.6		
Plastic	1		

Table 5-5 - Survey of materials present in central main systems for water distribution in countries of the European Economic Community (39)

Country	Cast iron (incl. bitumen lined)	Cast iron concrete lined	Steel	Asbestos/cement	Concrete (various types)	PVC/polythene	Others	Remarks
	Type of material (% of total)							
Belgium	40	-	13	40	-	7	-	
Denmark	50	-	-	10	-	40	-	*
France	74	-	4	6	4	12	-	
Germany Fed. Rep.	55	10	8	10	1	15	1	
Irish Rep.	41	-	3	30	2	24	-	*
Italy	2	-	80	15	-	3	-	*
Luxemburg	53	-	33	6	-	8	-	
Netherlands	27	-	4	46	1	22	-	
United Kingdom	71**	10	3	7	1	6	2	

* Approximate value

**About 45% concerns bitumen-lined cast iron pipes

Table 5-6 - Proportion of population in the European Economic Community using water transported through A/C pipe

Country	Population* 1 x 10^6	Per cent A/C pipe in systems	Population, 1 x 10^6 using water from A/C pipe
Belgium	9.86	40	3.944
Denmark	5.12	10	0.512
France	53.96	6	3.238
Germany, Federal Republic of	61.67	10	6.167
Irish Republic	3.44	30	1.032
Italy	57.20	15	8.58
Luxembourg	0.36	6	0.022
Netherlands	14.24	46	6.550
United Kingdom	55.83	7	3.908
Total	261.68		33.953 (~13%)

*1981 Data from UN World Statistics in Brief, 7th ed., New York, 1983.

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