Modelling the long term corrosion of reinforced concrete sewers

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Abstract Microbiologically influenced corrosion (MIC) of reinforced concrete sewer systems is a major issue for waste water authorities world-wide. Global repair costs are estimated at billions of dollars per year. Advanced stages of corrosion may trigger structural failure with potentially serious operational, economic and societal consequences. The fundamental issues involved in concrete sewer deterioration are reasonably well-understood but much less developed is the quantitative prediction of the rate at which deterioration is likely to occur under particular operating environments. An outline is given of a current industry-sponsored research project that aims to develop a phenomenological model of the sewer corrosion process for use in estimating the reliability and the expected remaining service life of concrete sewers. The model will be based on corrosion science but to ensure relevance to use in industry it will be calibrated to field observations and specific laboratory testing. This will also involve historical records and the experience of the industry participants. Parameters of particular interest include H_2S levels, temperature and humidity and the effect of odour control measures.
Keywords Concrete corrosion; sewers; bacteria; hydrogen sulfide; modelling

INTRODUCTION

When (reinforced) concrete is exposed to sewage directly or to the gasses in the space above liquid sewage, it eventually shows the formation of a soft white pasty material. Already in the late 1800s this deterioration was attributed to the chemical action of sulphuric acid (H_2SO_4) on the calcareous components of the concrete. The H_2SO_4 is the result of the oxidation of the H_2S gas generated by the sewage as it moves through the sewer system with the required oxygen being available in the sewer headspace since the sewage itself usually has a high biological oxygen demand (BOD). In addition to the purely chemical attack by H_2SO_4 it has been established that there is also a biological influence (see Vollertsen et al. 2008 for an extensive review). However, its importance did not become evident until the 1980s when there was a significant increase in the number of failures of sewers due to corrosion (Tator 2003).

The increase in failures can be attributed in part to the ageing of the sewerage systems and their gradual deterioration with time. However, it was also correlated with tighter restrictions imposed in the 1980s on the nature and toxicity of industrial wastewaters permitted to be discharged to sewers. This restriction significantly lowered the levels of biologically toxic metals (lead, chromium, mercury, arsenic, cadmium) in the sewage. As a result bacterial levels (and consequent MIC) were found to increase dramatically (Sydney et al. 1996). Increases in MIC also were linked to (i) increased use of household sulfate containing detergents (ii) higher sewage temperatures caused by the increasing use of domestic hot water and (iii) increases in sewer line lengths and thus sewage residence times as the suburban regions served expanded. These trends led to renewed interest in concrete sewer corrosion, given the need for sewerage authorities to stretch resources to service increasing populations without causing excessive failure rates and expensive and disruptive failures.

The present paper outlines part of a research program that aims to provide a predictive model for the longer-term deterioration of reinforced concrete sewers and which accounts for the major influencing environmental and operational factors. The model will be phenomenological, based on corrosion science and calibrated to a range of realistic field data and to laboratory observations obtained to elucidate specific aspects. Because the corrosion processes and the influencing factors are very complex, judicious simplifications in modelling and calibration are inevitable. The next section outlines, briefly, the fundamentals of the corrosion process in sewers and the key factors known to be involved. An outline is then given of the proposed modelling approach.

CORROSION OF CONCRETE SEWERS

A new concrete pipe has a high surface pH, around 12-13, a result of the cement-setting process. This means the concrete surface remains free from direct chemical attack until the surface pH is reduced sufficiently. However, the various pipe surfaces will be colonized by biofilms in which bacterial (and fungal) activity can occur. They are composed of extracellular polymeric substances (EPS). These are hydrated biopolymers of microbial origin forming a matrix in which microorganisms are embedded. The biofilm determines the immediate conditions of life for the microorganisms, their interaction and their interaction with their environment. EPS are composed of polysaccharides, proteins and other materials including DNA (Flemming et al. 2007).

Sulfate reducing bacteria (SRB) are known to become active within biofilms soon after the surfaces are first colonized by biofilm. SRB may be introduced by the wastewater but are known to be ubiquitous in the environment. Given sufficient nutrients, including organic carbon and electron donors (energy sources) such as sulfates (SO_4^-), all of which normally are abundant in sewage, the SRB produce hydrogen sulfide and carbon dioxide within the wastewater (Figure 1):

$$\text{Organic carbon} + SO_4^{2-} \xrightarrow[SRB]{} H_2S + CO_2 \tag{1}$$

The H_2S diffuses from the biofilm into the wastewater where around 65-75% dissociates, some of which escapes into the gas phase. Similarly, the CO_2 also diffuses from the biofilm into the waste water and some into the gas phase. Some of the gaseous H_2S and CO_2 will be transported through the headspace atmosphere by diffusion, advection and air velocity and condense on the concrete roof and wall surfaces of the pipe. These surfaces are wet as a result of the high humidity within the sewer and form weak carbonic acid $CO_2 + H_2O \rightarrow H_2CO_3$ that together with the acidic H_2S will react, slowly, with the alkalis in the concrete to lower the concrete surface pH with time. Evidently, the rate at which this occurs depends in the conditions within the sewer and its H_2S loading - 'a few years' is indicative.

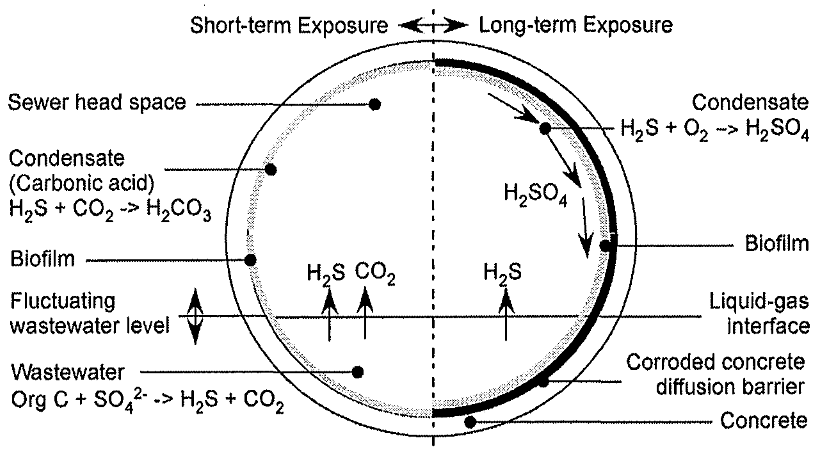


Figure 1. Schematic overview of chemical processes involved in the corrosion of concrete sewers.

When the surface pH drops to about 9 it becomes possible for bacteria such as the neutrophilic sulfur oxidizing microorganism (NSOM) *Thiobacillus* spp. to become active and oxide H_2S to sulfuric acid (H_2SO_4). This also will react with the concrete surface and further lower the surface pH. In turn this permits various other bacteria to become active. In practice there will be a succession of bacteria species that will dominate as the pH reduces. Eventually, when pH drops to about 4, acidophilic sulfur oxidizing microorganisms (ASOM) will find conditions appropriate for active metabolism and act to oxidize H_2S to H_2SO_4 and also to oxidize any thiosulfate ions ($S_2O_3^{2-}$) and perhaps elemental sulfur. This activity lowers the surface pH to around 2.

The deterioration of the concrete pipe surface begins as soon as the calcareous and the alkaline components of the cement of the concrete is attacked by H_2SO_4 and increases sharply with reduced pH (acidic conditions). The main reactions are:

$$H_2SO_4 + CaO.SiO_2.2H_2O \rightarrow CaSO_4 + Si(OH)_4 + H_2O \tag{2}$$

$$H_2SO_4 + CaCO_3 \rightarrow CaSO_4 + H_2CO_3 \tag{3}$$

$$H_2SO_4 + Ca(OH)_2 \rightarrow CaSO_4 \,.\, 2H_2O \tag{4}$$

The major corrosion product, gypsum ($CaSO_4.2H_2O$), has a volume some 24% greater than its constituents and weakens the concrete structure. It also may react with the tri-calcium-aluminates present in the concrete cement matrix, to form Ettringite ($CaO.Al_2O_3.3CaSO_4.31H_2O$) that has a much higher (2-7 times) volume expansion and is thus very destructive:

$$CaSO_4 + 3CaO.Al_2O_3.6H_2O + 25H_2O \rightarrow 3CaO.Al_2O_3.3CaSO_4.31H_2O \tag{5}$$

Both volume expansions cause cracking of the concrete surface, thereby facilitating the transport of moisture, acid and bacteria into the increased internal surface area of concrete and leading to further damage. Quite separately there is a soft weak, whitish external layer of corrosion product, primarily gypsum from reaction (4). Although it can harbour microorganisms, most likely the gypsum corrosion product layer acts as a diffusion barrier that thickens as the corrosion process continues (Okabe et al. 2007). This will affect the diffusion of the H_2SO_4 that condenses on the sewer walls but also the diffusion of nutrients necessary for microbial activity (Figure 1).

The factors that influence the rate of internal corrosion of concrete sewers follow easily from the above description of the processes involved. Table 1 gives a summary based on Wells et al. (2009).

Table 1. Known influencing factors that increase concrete corrosion in sewers

Factor (increase)	Description of effect (increase assumed)
Temperature of sewage / headspace atmosphere	vaporization of H_2S from liquid to gas phase and MIC microbial activity and MIC
Sewage H_2S	overall H_2S in system and MIC
Humidity in headspace	condensate in headspace and MIC
Sewage pH reduction	vaporization of H_2S from liquid to gas phase and MIC
Sewage Turbulence	vaporization of H_2S from liquid to gas phase and MIC
Sewage BOD	anaerobic (SRB) microbial activity and MIC
Residence Time	anaerobic (SRB) microbial activity and MIC
Location in sewer	crown and waterline regions
Water/cement ratio	diffusion of aggressive species
Porosity/permeability	diffusion of aggressive species
Cement content reduction	reactivity of concrete
Calcareous aggregate	reduces reactivity of aggressive species
Washing of sewer walls	Temporarily reduces microbial activity and MIC for a few weeks
Chemical odour control	Provides nutrients and increases microbial activity and MIC

MODELLING APPROACH

Of primary interest to sewage authorities is the viability of the sewer to transport sewage satisfactorily and without structural failures for as long as possible and how this might be influenced by different operational conditions including odour control measures. Since inspecting long lengths of sewers is expensive and the inspection process not known for high accuracy in estimating corrosion losses, it is desirable to have some means of predicting the likelihood of significant corrosion. Thus if the sewer is currently operational and apparently satisfactory in operation, the next question is 'how long before it becomes unsafe?' and, therefore, 'at what rate will it be corroding in the future?' The problem can be illustrated using the hypothetical corrosion loss curve shown in Figure 2. The likely future rate of corrosion (AC) at some point in time t_i corresponding to observation A requires knowledge, or an estimate of, the corrosion loss behaviour (OAC). Evidently, simple linear extrapolation (OAB) from the origin and the current observation (i.e. A) is not helpful since the corrosion loss – time function is seldom linear. The differences in likely future corrosion losses predicted by AB and AC can have a significant economic and operational outcomes. Estimation of the likely long-term rate AC requires knowledge of the underlying model (OAC).

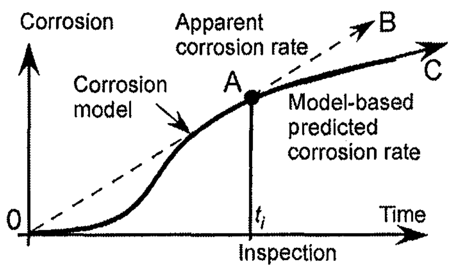


Figure 2. Hypothetical corrosion loss curve OAC showing the large difference in most likely future corrosion rate AC and the extrapolated rate OAB for corrosion information obtained at time t_i.

In attempting to obtain models for prediction, engineers traditionally have used empirical relationships derived from observations of corrosion loss and the various factors/parameters thought to influence it. Usually a linear relationship (the 'corrosion rate') or a simple curve is assumed, often ignoring or discrediting data that does not fit. In its simplest form this reduces to drawing a curve of 'best fit' through data points. In the atmospheric corrosion literature, for example, there is a long history of application of linear correlation for model development. However, the poor correlation coefficients shown that it has been less than successful - there are just too many parameters, poorly defined. Moreover, the underlying linearity assumptions are highly likely to be incorrect. This approach also provides little insight about the possible effect of changes outside the experience base or about the uncertainty in model predictions (Melchers 2009).

Ideally, models are based on more than just data. They should be based on, or at least be consistent with, fundamental principles. This includes the physical-chemical aspects of corrosion, the microbiological effects and how these evolve with time as the corrosion process proceeds, the external and internal factors that are involved, etc. For metal corrosion, serious modelling efforts built on theoretical issues and electrochemistry are currently being made, using on understanding of the processes involved. Some of this uses data from laboratory experiments. However, for real-world application, it is necessary to extrapolate from the short-term laboratory experiments to the long-term corrosion expected in-situ, since only this is of real interest. Similar issues apply for the corrosion of sewers. It raises difficult questions but it is clear that field data is essential.

For sewer corrosion there are still significant gaps in the necessary basic understanding of the processes involved (Wells et al. 2009). Some mathematical modelling has been attempted (Bohm et al. 1998) but to date without microbiological aspects. Unfortunately, this type of modelling requires a multitude of parameters many that are unlikely ever to be available for a particular sewer (system). This is particularly the case for biological aspects (Roberts et al. 2002).

A more practical approach is to hypothesize a model based on observed physical behaviours of sewer pipes and on known corrosion theory, including the electrochemical, physical chemistry and microbiological fundamentals. This 'phenomenological' model can be turned into a mathematical model to interpret trends in observed data - asking 'can the data be interpreted as being consistent with the *(a priori)* model', and using it to calibrate the model to real-world data (Figure 3). A generally similar concept has been used successfully for modelling corrosion of steel in marine environments, including microbial aspects (Melchers 2003, Melchers and Wells 2006). This, essentially Bayesian, way of proceeding obviously is completely different from the traditional one in which the data are somehow sacrosanct and the data points being the only pieces of information with real value. Also, it implies that inevitably there is uncertainty associated with each data point and that some data points might be 'wrong' owing to errors in observation or data processing.

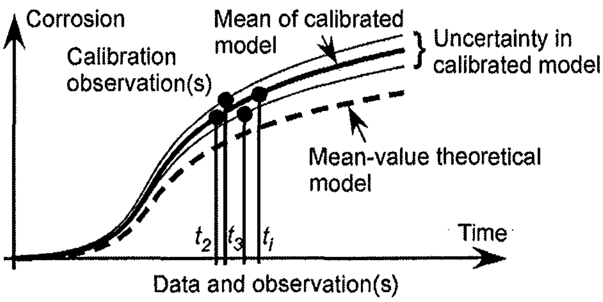


Figure 3. Schematic diagram showing the theoretical nonlinear corrosion model calibrated to data. This also shows the remaining uncertainty in the model after calibration.

The phenomenological model describes the likely corrosion loss as a function of exposure time, sewer average internal environmental conditions and material characteristics (Table 1). Typically the relationship changes with time. Thus, the incubation period when surface conditions at the concrete adjust to the wastewater environment or to the headspace atmosphere is eventually followed by concrete deterioration under direct H_2S and H_2SO_4 attack. The resulting build-up of corrosion products then influences the rate of the deterioration. This can be modelled as a moving boundary-type problem (cf. Bohm et al. 1998). Models for steel corrosion show that microbial aspects also can be included (Melchers 2003, Melchers and Wells 2006).

A potentially important aspect is the mechanics of concrete component breakdown. With time the attack front moves further into the outer layer of deteriorated concrete and this creates new opportunities for further chemical attack and for colonization by bacteria. It also impedes the flux of nutrients towards bacteria and ions created by the breakdown of the cement and of the aggregates at the attack front away from the attack sites. The interfaces between the various components also must be considered (Figure 4). Again these are likely to be governed mainly diffusion issues. Previous experience indicates that it will be sufficient, for engineering purposes, to use one-dimensional modelling - i.e. perpendicular to the corroding surface. Also, the model will be developed in stages, commencing with a simple case and adding as new information and understanding becomes available (cf. Melchers 2009).

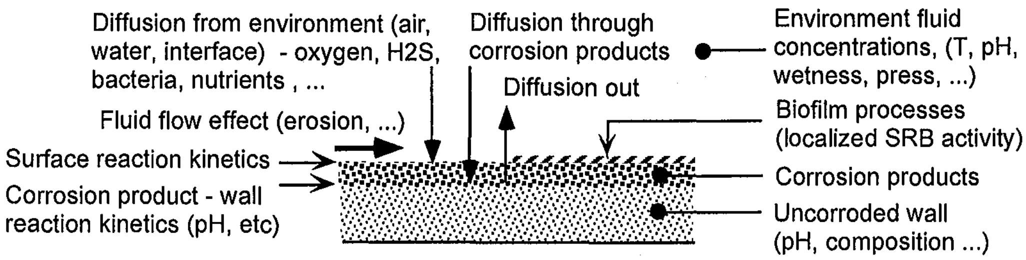


Figure 4. Schematic view of the main factors involved in the corrosion of concrete in sewers.

Since uncertainties always are present in data and less than 'perfect' data typically must be used in any in model calibration, a probabilistic corrosion modelling approach is appropriate (Melchers 2005). Figure 3 shows that after calibration of the 'a priori' or theoretical model to data, some degree of uncertainty remains, mainly from the scatter in the available data. This results from the natural variability in observations and the impossibility of accounting for all possible influencing factors. It reflects also that models are just that – models that can only imperfectly represent reality. Mathematically this can be formulated as a probabilistic function:

$$c(t,\mathbf{E}) = b(t,\mathbf{E}).f(t,\mathbf{E}) + \varepsilon(t,\mathbf{E}) \tag{6}$$

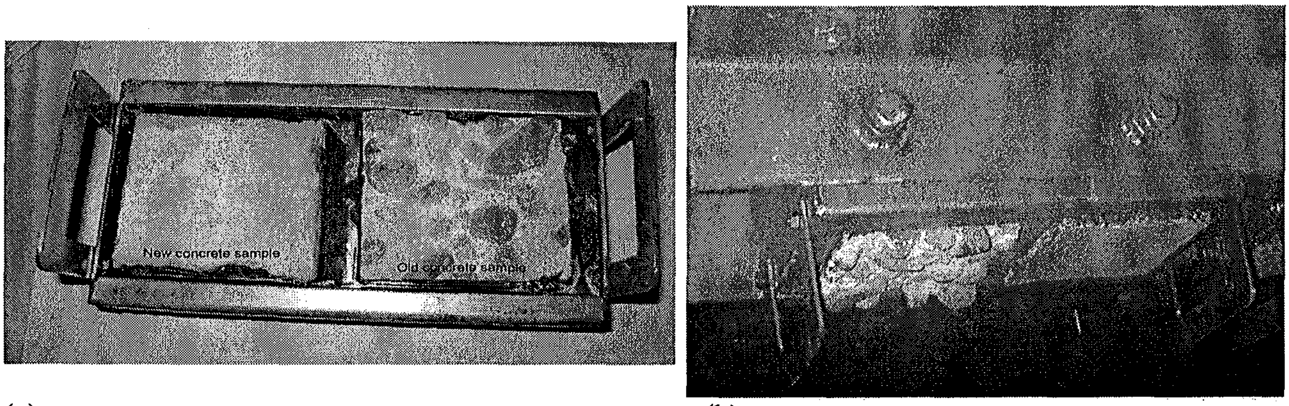
where $c(t,\mathbf{E})$ is corrosion loss as a function of t, the elapsed time and $\mathbf{E}$ the vector of environmental influences and material parameters. Also, $b(t,\mathbf{E})$ is a bias function (usually about unity for good quality models), $f(t,\mathbf{E})$ is a mean-value function representing expected corrosion loss and $\varepsilon(t,\mathbf{E})$ is a zero-mean error function. Evidently, the main emphasis in model development should be on the mean-value function $f(t,\mathbf{E})$. If this is a poor choice, the calibration to real data will produce a poor fit between model and data and thus produce a large $\varepsilon(t,\mathbf{E})$ term. Conversely, a high quality model should produce a good fit to the data and leave only a small $\varepsilon(t,\mathbf{E})$ term.

The task of developing the mean-value function $f(t,\mathbf{E})$ currently is on-going, focussing first on typical conditions and using material already available in the literature. The other task is estimating $\varepsilon(t,\mathbf{E})$ - in this respect the existing sewer corrosion literature is almost devoid of information. Data is currently being obtained from older corroded sewer concrete to make suitable estimates.

MODEL CALIBRATION

Initially, data already available in the literature and to be sourced from the files of industry partners will be used to attempt to calibrate the model. This will provide initial understanding of the relative importance of the variables where this is not already known. It will allow the model to be adjusted in a trial and error process as new data becomes available, both from in-situ and from specially-designed laboratory trials, until such time as reasonable convergence between all sources of data and the model predictions is obtained. It may mean that critical processes will need to be re-modelled as our understanding grows. Particularly important is the availability of long-term field data for which environmental conditions are known. For this reason a range of data, including that for very old concretes, exposed for long periods, is essential.

The field studies include exposures at three sites (cool, temperate and warm sewage). At each site specially-made stainless steel coupon racks hold one sample each of both new and 35 year-old concretes. The samples are mounted in resin so as to expose only one face to the sewer environment (Figure 5). The new concrete was sourced from industrially-produced spun concrete pipes. The old concrete samples were cut from partially corroded concrete covers removed from a large sewer manhole. More than 300 samples have been installed, mostly on the crown of the sewer. At one site an additional set of coupons have been installed just above the normal water level. This is to ascertain the effect of position within the sewer.



(a) (b)

Figure 5. (a) Plan view of stainless steel coupon rack showing new concrete (left) and old concrete (right) and (b) typical coupon rack mounted on the crown of a sewer.

The coupons will be removed at 6-12 monthly intervals over the 5 year test period. On recovery they will be examined for biofilm microorganisms and the chemistry of the corrosion layer. Also, the pH and mineralogy, elemental composition and structure will be determined for each sample, using a variety of techniques. Sulfide consumption rates will be determined by measuring the sulfate concentration in the corrosion layer. In addition to coupons, for some older sewers it will be possible to drill cores from the sewer wall. Overall concrete loss and changes in surface profile will be determined using photogrammetry of the surfaces before exposure and again after exposure and the differences noted (Wells et al. 2009). The analysis of the coupons on recovery will be a joint venture between the Universities of Newcastle and Queensland (Figure 6).

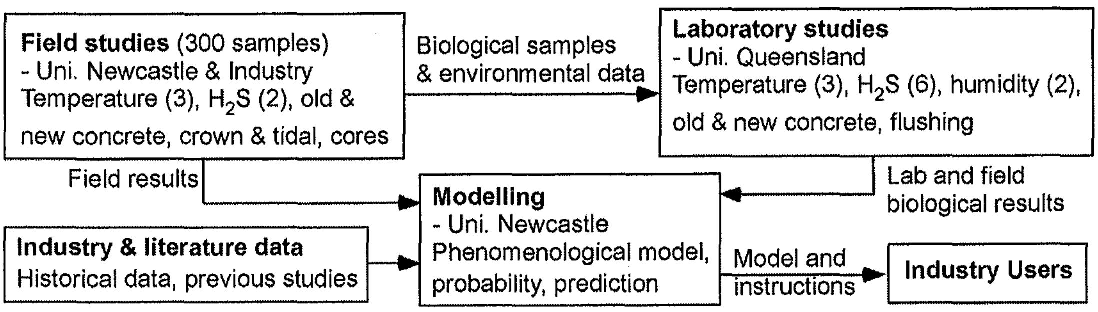


Figure 6. Studies and interactions for data and modelling of sewer corrosion.

Laboratory exposures in natural but pH buffered sewage are being conducted in parallel with the field exposures (Figure 6). The first priority is to attempt to replicate the field results, to ensure validity of further laboratory studies. These will quantify the effect of a number of variables not practical to consider under field study conditions (Figure 6) as well as to consider more fundamental aspects of biofilm formation and microbial dynamics. This will include the use of microsensors to measure solute (O_2, H_2S, pH) distribution profiles, denaturing gradient gel electrophoresis (DGGE) to provide profiles of the microbial communities and determination of nutrient levels in the biofilm waters by HPLC analysis for oxalic, gluconic and citric acid.

CONCLUSION

The interaction of microbiological agents and chemical processes within concrete sewers is known to be a significant global problem for wastewater system deterioration. This paper has outlined the main characteristics of a project that seeks to develop mathematical models for the prediction of likely future corrosion as a function of exposure time and of the exposure environment, as influenced also by odour control measures. An outline is given of the in-situ field testing program being run at 6 different locations in operational sewers and of the complementary laboratory program that aims to elucidate aspects that cannot be studied in-situ. A range of chemical and biological testing will be done to provide input to the modelling process. The model also will include historical data and experience obtained from the Australian wastewater industry.

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