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Modeling the Thermal Stratification of Water Filled Mine Pits

By:

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MANAGEMENT PERSECTIVE

Abandonment of mining pits can pose a potential enviromental problem if there is an outflow from the pit and if this discharge contains toxics in exceedance of standards. Unlike natural water bodies mining pits have depths of the order of the horizontal dimensions and can have very steep shorelines which shelter the surface atmospheric forcing. No literature on the water quality modelling of such water bodies exists. Our study has been was prompted by need identified by the Environmental Protection Service, DOE, for tools for the assessment of potential water quality problems arising from the abandonment of mining pits and was funded through a grant from MEND.

This report was prepared for Mining Reclamation Meeting in Vernon B.C. jointly with some researchers from the University of British Columbia and presents a progress report on our initial attempt to mathematically model the water quality of a mining pit. At this early stage we provide no new results. We intend to further model this pit once our data gathering in the Brenda Mine Pit is completed.

Modeling the Thermal Stratification of Water Filled Mine Pits

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Abstract

Meromixis, where a stratified body of water rarely mixes completely throughout its depth, is considered beneficial for containment of undesirable chemical species in water filled abandoned mine pits. Here we discuss a modeling effort examining the development of the thermal stratification in such a body of water.

The model is a simple algorithm based on a one dimensional diffusion equation. The heat fluxes and boundary conditions are discussed as well as the mechanisms affecting turbulent diffusion and penetration of the mixed layer. This is especially important in the prediction of possible fall and spring overturns.

The model is described in the context of the Brenda Mines Pit near Peachland. The temperature data does not strongly indicate meromixis, however, dissolved oxygen measurements show there might be a barrier to vertical penetration of heat and momentum.

§1. INTRODUCTION

Vertical stratification of temperature and chemical composition is a ubiquitous feature of oceans, lakes and reservoirs. Theory and data from from the fields of research of Oceanography and Limnology are used as the basis for predictive modeling. Knowledge of the the physical behaviour of water filled mine pits is of importance because density stratification serves to contain undesirable chemical species held in the water column.

Wetzel (1983) states that

> a number of lakes do not undergo complete circulation and the primary water mass does not mix with a lower portion. Such lakes are termed meromictic. In meromictic lakes, the deeper stratum of water that is perennially isolated is the monolimnion... The two strata are separated by a steep salinity gradient which is called the chemocline.

Thus, it is expected that it is desirable that a water filled mine pit be *meromictic*.

However, at least in the context of existing understanding, water filled mine pits exhibit several special properties,

(i) they have a relatively large average depth to width ratio,
(ii) the steepness of the shoreline leads to a complicated wind field,
(iii) the equation of state is not easily obtainable, and
(iv) locally they freeze over in winter.

These properties and those normally expected are synthesised in Figure 1.

The objective of this research is to develop a simple model that examines the development of the stratification over the year. As such it examines only the physical mechanisms at work; although it is noted that chemical dynamics must play a role in the development of the equilibrium density profile. This model is described in the context of the Brenda Mine Pit, near Peachland in British Columbia.

§2. DEVELOPMENT OF THE THERMAL STRUCTURE

The approach we take here is to build a model that is a time-varying description of the vertical temperature structure of the mine pit. The vertical variation in plan area is accounted for implicitly.

The vertical temperature distribution $\Theta(z)$ over depth z ($z = 0$ is the water surface, $z = h$ is the bottom) can be described by the following conservation equation,

$$\underbrace{\frac{\partial \Theta}{\partial t}}_{(i)} + \underbrace{w\frac{\partial \Theta}{\partial z}}_{(ii)} = \underbrace{K_z\frac{\partial^2 \Theta}{\partial z^2}}_{(iii)} + \underbrace{Q(z)}_{(iv)}, \tag{1}$$

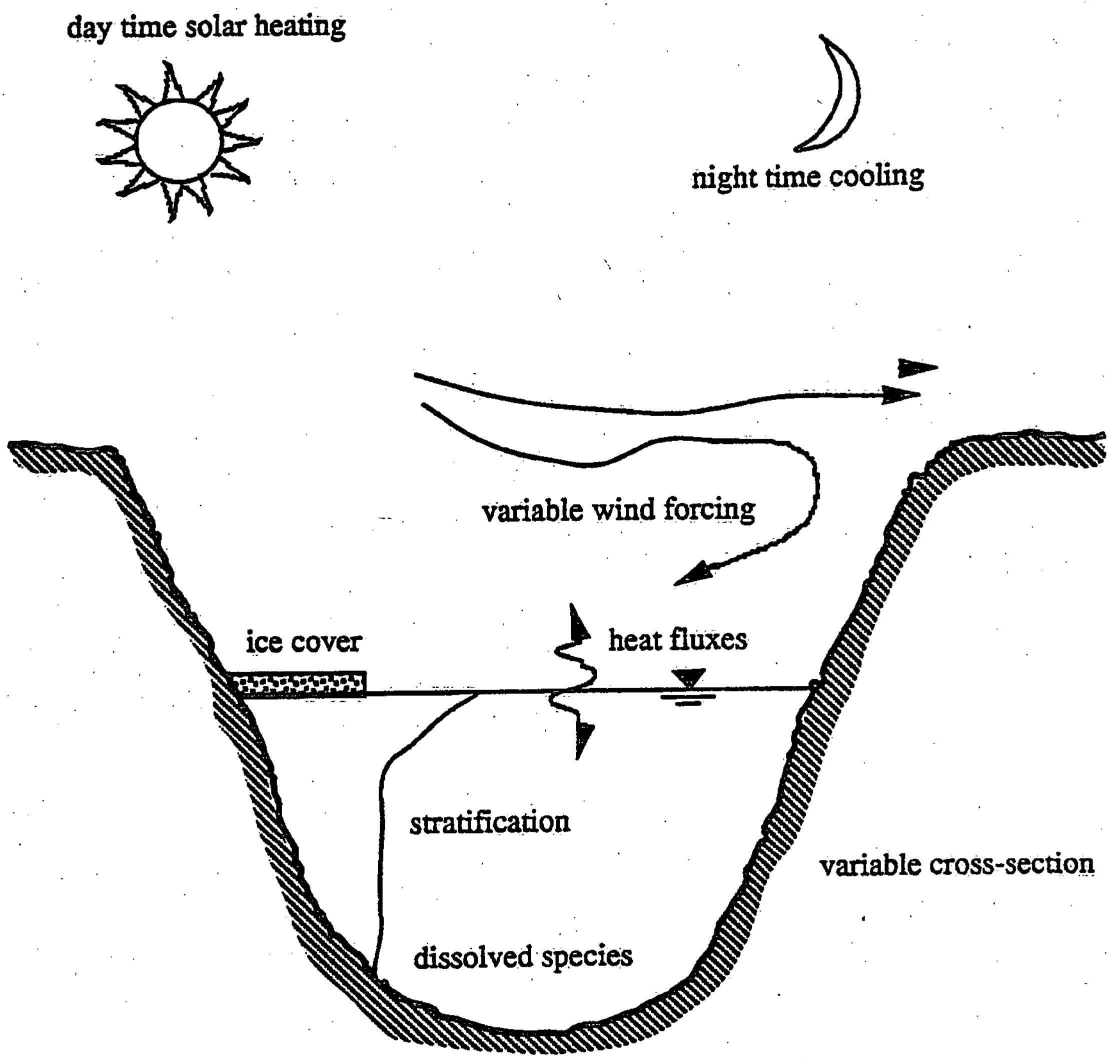

Figure One: A schematic illustration of processes affecting a water filled mine pit.

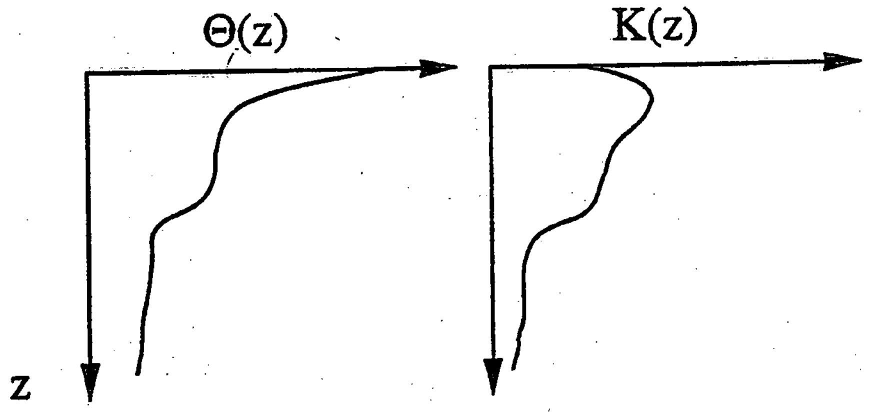

Figure Two: Illustration of vertical distributions of temperature and diffusivity in summer.

where t is time, w is vertical velocity, K_z is vertical diffusivity, Q is a heat source term and $\partial/\partial x$ and $\partial/\partial t$ are partial derivative operators.

We need to solve this equation for Θ. First let us discuss the elements of the equation with respect to Figure 2. The time rate of change of temperature is described by (i); it is this term that we will use in the model to step from one time to the next. The second term (ii) describes the advection of fluid of different temperature past the level point of consideration, z. This term can be ignored for two reasons, firstly the stratification retards vertical velocities and secondly, any vertical motion that does exist will probably be turbulent and thus be incorporated into K_z. The distributive properties of any turbulence and the efficiencies are all contained within the diffusion term (iii). This term assumes that turbulent diffusion can be described by the same functional distribution that exists for molecular diffusion; thus the *second* vertical derivative of Θ controls the process. In addition the effects of wind stirring, night time cooling and penetrative convection are all held within the distribution of K_z. Here we will use

$$K_z(z) = \frac{q_*^2}{N} \tag{2}$$

to describe the distribution of diffusion (Fischer 1979). The q_* term is a velocity derived from the velocities generated by the wind and by the night time cooling. The buoyancy frequency, N, is a measure of the strength of stratification. It is formally given by

$$N^2 = \frac{g}{\rho_0}\frac{\partial \rho}{\partial z} \tag{3}$$

where g is gravitational acceleration, ρ_0 is an average density and $\partial\rho/\partial z$ is the vertical gradient of density. Obviously we need to be able to describe the equation of state (the equation that describes the density as a function of its components and *in situ* conditions). Here we will use the equation of state for seawater as a first approximation to the actual equation of state. This approach has the potential to estimate the effect of different chemical composition on the insitu density. The remaining term Q describes the amount of heat energy that enters the water column *beneath* the surface. This is described more completely below.

The forcing controls the system. We split this into three possibilities and they are (i) day time heating without ice cover, (ii) night time cooling without ice cover and (iii) day or night cooling with ice cover. Here we initially ignore the possibility of heat from ground water fluxes. Rogers (1992) and Patterson and Hamblin (1988) describe the complexity of fully capturing the thermal dynamics of ice covered lakes for the range of latitudes covering British Columbia. The response of the stratification to day and night time heat fluxes have received significant treatment in the literature (Kraus and Turner, 1967 Imberger 1985) as well as the complication occurring near the temperature of maximum density (Wiegand and Carmack 1981).

We will split the heat flux into two components, one that simply forms a boundary condition that controls the values of $\Theta(z=0)$ and $\partial\Theta(z=0)/\partial z$ and a penetrative term that provides internal heating through Q. This term is split into several spectral bands so that

$$Q = \sum_{i=1}^{N}\left[e^{-\beta_i z}\frac{\beta_i H_i^*}{\rho_0 c_p}\right] \tag{4}$$

where β_i (m^{-1}) and H_i^* (Wm^{-2}) are the extinction coefficient and the radiative heat transfer for the ith spectral band. The c_p ($\mathrm{J.kg^{-1}.C^{\circ -1}}$) is the specific heat content for water. Typically between $N = 1$ and $N = 3$ is sufficient to capture the effects of this transfer.

§3. OBSERVATIONS FROM BRENDA MINE

Brenda Mine Pit is an exhausted open-cut mine near Peachland in the Okanagan Region. At its deepest point it is over 100 metres deep. At the water surface (as of December 1993) it is, on average, 800 metres in diameter. Figure 3a shows the depth contours and the relatively steep walls. The variation in average cross sectional radius is roughly linear and shown in Figure 3b. This suggests an average aspect ratio $h/L \approx 0.2$, where L is the average horizontal lake dimension, compared to a typical Limnological value of the order of 10^{-3}.

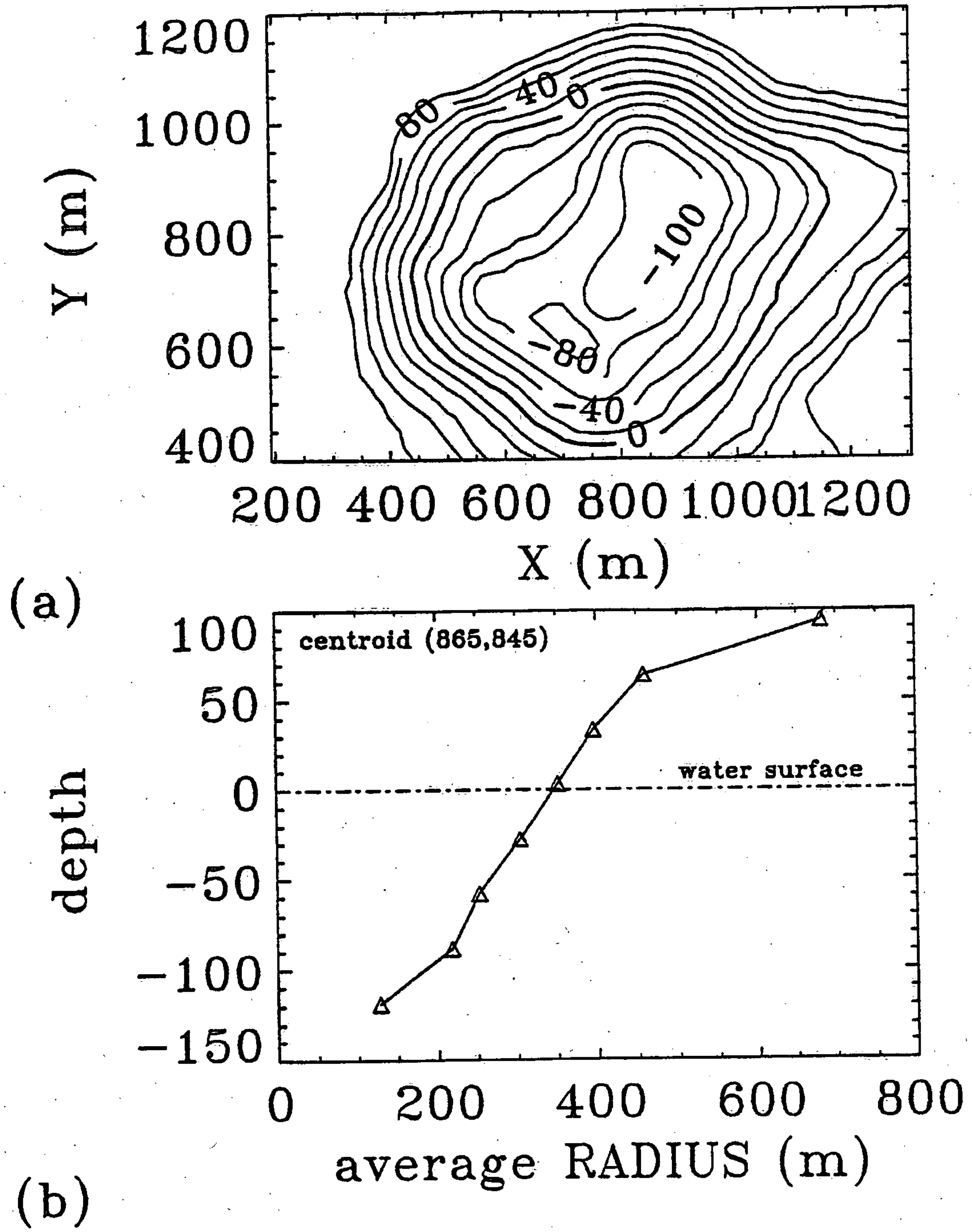

Figure 3 (a) Depth contours at twenty metre intervals for Brenda Mine, the 0 metre contour represents the water depth in December of 1993, (b) averaged radius of the pit above and below the water surface.

Brenda Mines have recorded nearly a full years worth of data extending from August 1992 through to October 1993. The ice cover first appears in mid-November and remains on for approximately four months until early April. There is a gap in the data for a proportion of this time. The data resolution is such that it provides information at roughly monthly intervals at 10 metre intervals over the depth of the water column.

Temperature and dissolved oxygen data contoured in Figures 4 a and b provide possibly opposing indicators of the state of the water body. The temperature contours definitely indicate full overturn in that the temperature of maximum density exists over the full depth of the water column some time during the no-data period and later mid-April. Contrarily, the dissolved oxygen distribution indicates a relatively well contained distribution that penetrates to over 60 metres by early February. Calculation of percent saturation indicates that the dissolved oxygen is near full saturation at the surface early in April and closer to 40 % at 50 metres depth in early February. Thus, solubility is not a barrier to vertical penetration of the dissolved oxygen.

§4. DISCUSSION

The crux of a successful model is the parametrization of the turbulent velocity scale q_* from equation (2). This requires accurate parametrization of the efficiency of mixing. MacIntyre (1993) puts some of the existing results into a useful context by clearly defining how mixing efficiency is related to diffusivity and to circulation timescales. However, correct facilitation of the mechanisms in a numerical model requires well resolved field data. This is not available here and is unlikely to be available for any other mine pits. Consequently crude efficiencies of energy transfer must be applied. These are readily available in the literature (MacIntyre 1993) but care must be taken that the correct efficiency is used for the particular entrainment mechanism.

The steep lake walls suggest that the effect of the wind should be deemphasised in favour of penetrative convection. The process occurs when the surface heat flux is such that the very surface water becomes more dense than that beneath it. It must then fall to its level of neutral buoyancy, As it falls it loses energy to mixing, turbulence and viscosity. This mechanism, combined with the change in plan area of the pit with depth (Figure 3b) implies that if the convection mechanism can penetrate deep into the water column its relative effectiveness will accelerate with depth.

We can speculate on the apparent conflict indicated by the temperature and dissolved

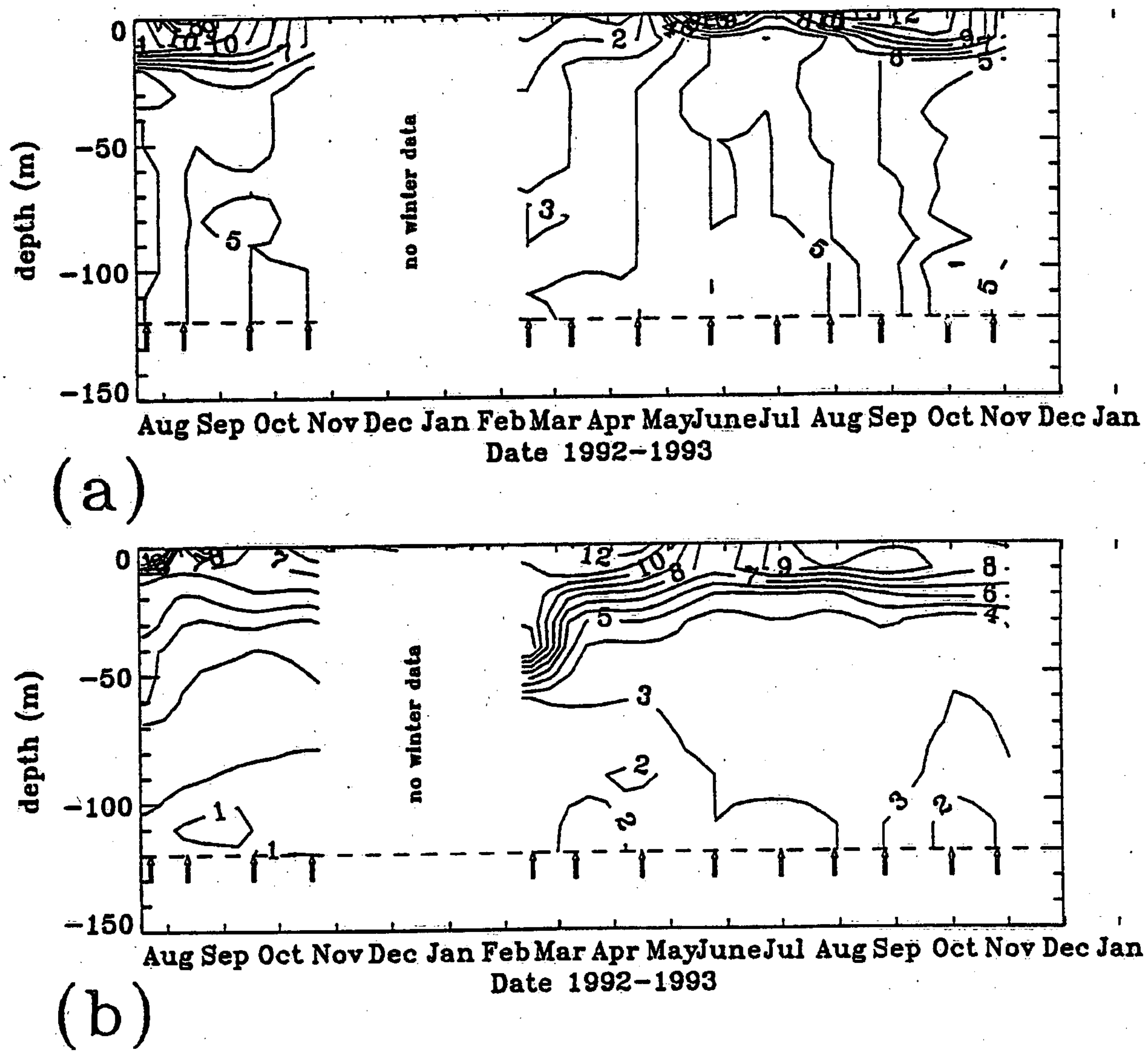

Figure 4 Contours of (a) temperature (°C) and (b) dissolved oxygen (ppm) from the Brenda Mine Pit.

oxygen contours of Figure 4. Possibly the answer lies in the temporal and spatial resolution of the data. Returning to the contours of Figure 4 the profile of most interest was taken in mid-April of 1993. At this time there is still probably ice cover and the top 25 metres of the water column are weakly stratified (with temperatures less than 4°C). However beneath this surface layer the water column is at the temperature of maximum density. At ice-off the surface temperature quickly increases above 4°C so that, at some time late in April, the water column was effectively homogeneous at least in thermal stratification. Yet the dissolved oxygen data show a well behaved distribution over the top 40 or so metres at this time. We must conclude that, either there is a problem with the oxygen sampling, or there are sufficient salts dissolved to provide a dominating component to the density profile or possibly sampling during the day captures only the stabilising step in the stratification development and the inherently unstable night time cooling is being missed.

This paper describes the basic principals and mechanisms behind modeling the vertical thermal structure of water filled pits. We highlight the differences between these pits and more traditionally studied stratified fluids. Finally, we illustrate some results from a mine pit and identify apparent anomalous behaviour.

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