BIO-WALL TECHNOLOGY: CONCEPTUAL DESIGN AND ANALYSIS

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ABSTRACT

In-situ bioremediation is a process by which contaminants in subsurface environments are biologically eliminated or mineralized; however, it is often difficult to implement. Microbes sparsely distributed in deep soils are incapable of degrading a chemical rapidly; furthermore, fine-pore structures of soils tend to retard the penetration and propagation of these microbes and to hinder oxygen transfer. The latter is particularly detrimental to the aerobic growth of microbes, which is often essential for bioremediation. Measures intended to promote bioremediation, such as addition of surfactants for enhancing dissolution and application of genetically-engineered microbes for accelerating the biodegradation of the contaminants, are almost impossible to adopt. This is attributable to the fact that various facets of the bioremediation process, e.g., the distribution of dissolved contaminants, nutrients and oxygen, and the concentration of microbes, can not be readily manipulated.

The present work proposes a novel technology, namely, bio-wall. This technology resorts to an in-situ constructed medium with porosity and organic content greater than those of the original soil for promoting the adsorption and retention of microbes and the biodegradation of contaminants. Moreover, oxygen and nutrients are supplied to the bio-wall to facilitate microbial growth. The results of a conceptual design study and simulation have revealed that the technology is indeed feasible and, under certain environmental conditions, cost-effective. Particularly noteworthy is the fact that the bio-wall can prevent contaminant migration through enhancement of the biodegradation rate and reduction of the plume-distance, both by several orders of magnitude.

KEY WORDS

bio-wall, remediation, soil, biodegradation

INTRODUCTION

Manufacture, transportation and consumption of organic chemicals have frequently caused soil to be contaminated, thus posing serious environmental threats. Remediation of organic-contaminated soils has indeed become urgent; however, it can often be costly. Conventional methods of remediation, such as pump-and-treat, soil excavation and incineration, have numerous drawbacks including high cost, risk of exposure to contaminants, and difficulties of final disposal. On the other hand, in-situ bioremediation has been demonstrated by laboratory experiments and pilot field studies to be a potentially cost-effective technology (see, e.g., [1, 2]). In principle, it is capable of permanently restoring or reclaiming a contaminated site with little environmental impact. It appears, however, that successful implementation of strictly in-situ bioremediation has seldom been achieved [3]. Frequently, biodegradation is not suitable for local environments in subsurface soils because it does not proceed at a satisfactory rate. In general, the deeper the location in the soil, the smaller the microbial population. Moreover, fine-pore structures of soils substantially retard the convection and propagation of microorganisms as well as the transport of inorganic nutrients and oxygen. Field investigations have revealed that compositions of oil deposits in some

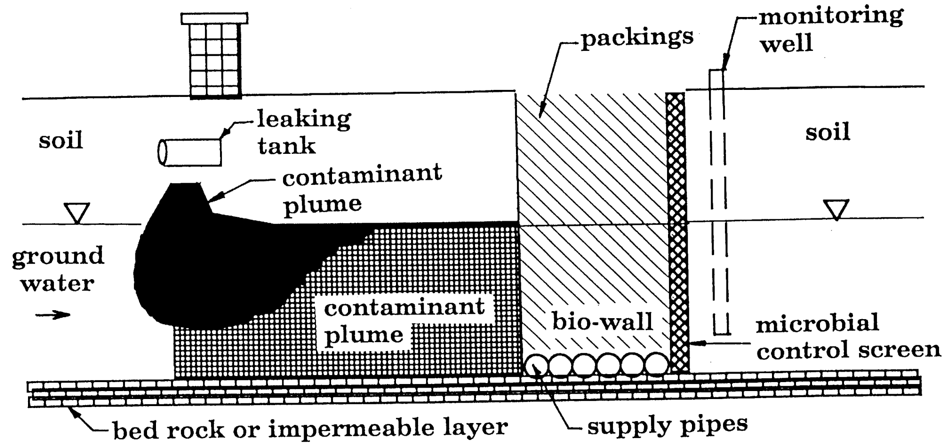

Figure 1. Basic design of the bio-wall.

landfills did not change even after forty years [4]. Above-ground as well as underground constructions, including buildings, highways, buried cables and sewer pipes, are serious barriers to implementation of in-situ bioremediation. This paper introduces a novel technology, namely the bio-wall technology, to lessen the difficulties involved in the remediation of contaminated ground water and subsurface soils.

Bio-wall refers to an in-situ constructed trench packed with materials that effectively promote biodegradation; it is schematically represented in Figure 1. At a contaminated site, the trench is placed downstream of the contamination and cuts across the potential trajectory of any contaminant plume. The contaminated site can also be surrounded by the bio-wall if the ground water flow is irregular or when there is no prevailing flow pattern.

CONCEPTUAL DESIGN

To construct a bio-wall, soil is excavated to create a trench. This trench is then packed with a mixture of sand, rocks, wood chips, sewage sludge and other materials, e.g., controlled-release devices containing nutrients (see, e.g., [5]), that facilitate microbial growth. Naturally, the organic contents of the media packed in the trench tend to be higher than those of the original soil. Furthermore, the pores of the media are larger than those of the soil, thereby substantially elevating the packed trench's hydraulic conductivity or permeability. Hence, the bio-wall does not significantly affect the ground water flow pattern including the direction and velocity of flow. The packings provide surfaces for cells to attach themselves and to form colonies. Immobilized cells on solid surfaces are protected from washout; moreover, they grow to higher densities than those in suspension cultures. The packings also serve as sources of natural carbon for sustaining the microbial populations. Air is pumped through a layer or several layers of horizontally-installed pipelines to supply oxygen and to strip the volatile organic compounds. Since oxygen is steadily transferred from the air to water, its concentration can be maintained at a reasonable level in the bio-wall. Generally, soil has an abundance of nutrients and minerals; nonetheless, additional nutrients can be supplied through the pipelines if needed. Temperature and pH can be controlled by supplying heat and buffer solutions, respectively. Thus, the physical and biochemical conditions can be readily manipulated to promote biodegradation of contaminants in the bio-wall. A microbial control screen is optional at the outlet of the bio-wall. The screen can be a grid of small perforated pipes through which disinfectant such as chlorine or ozone can be injected into the ground water. The screen may also be substituted by a thin bed of triiodide-disinfection resin beads [6]. The function of the screen is to sanitize out-flow water and to prevent pathogens from propagating out of the bio-wall downstream.

Design equations

A quantitative description of biodegradation in the bio-wall is obtained through mass balances for participating species in a control volume. Both oxygen and nutrients are supplied at sufficient rates; thus, it is reasonable to assume that the rate of biodegradation is not limited by their concentrations, but depends only on the concentrations of substrates, i.e., the contaminants, C_{si}'s, and biomass, C_b. This gives rise to the following set of performance equations for the bio-wall [7].

$$\frac{\partial C_{si}}{\partial t} = \nabla \bullet \left(\overline{\overline{E}}_{si} \bullet \nabla C_{si}\right) - \nabla \bullet (\overline{u}\, C_{si}) + \frac{k_{si}\, a}{\varepsilon}\left(\frac{q_{si}}{K_{dsi}} - C_{si}\right) - \frac{\mu_{mi}}{Y_{si}} R_b C_b \left(\frac{C_{si}}{K_{si} + C_{si}}\right) \quad (1)$$

$$\rho \frac{\partial q_{si}}{\partial t} = -ak_{si}\left(\frac{q_{si}}{K_{dsi}} - C_{si}\right) \quad (2)$$

$$\frac{\partial (R_b C_b)}{\partial t} = \nabla \bullet \left(\overline{\overline{E}}_b \bullet \nabla C_b\right) - \nabla \bullet \left(\overline{u}\, C_b\right) + \sum_i \mu_{mi} R_b C_b \left(\frac{C_{si}}{K_{si} + C_{si}}\right) - k_d R_b C_b \quad (3)$$

The notations in these and other equations are fully elaborated in the nomenclature section.

A bio-wall constructed in soil creates several distinct interfaces whose boundary conditions need to be derived from the continuity of concentrations and that of mass fluxes [7]. Equations 1 through 3 can be solved, subject to these boundary conditions and the appropriate initial conditions. This determines the concentration profiles and local organic carbon consumption and eventually the required amounts of oxygen and nutrients, all of which are essential for designing and operating the bio-wall.

Basic design

The assumption of uniform physico-chemical and microbial properties in a bio-wall can substantially simplify the design equations. This assumption is justifiable in the light of the fact that the air bubbles rise through the porous media, thereby inducing vertical pore-water flow and effective mixing. For simplicity, a system with one contaminant, i.e., a one-component system, is considered here. For designing this system, the following additional assumptions are imposed: a. steady-state biotransformation; b. uniform biomass distribution; c. equilibrium adsorption-desorption; d. one-dimensional ground water flow; and e. negligible axial dispersion. Under these assumptions, Equation 1 becomes

$$\frac{d(uC_s)}{dx} = -\frac{\mu_m}{Y_s} R_b C_b \left(\frac{C_s}{K_s + C_s}\right) \quad (4)$$

To integrate this equation, let the position of inlet flow be x = 0 where $C_s = C_0$; then,

$$K_s \ln\left(\frac{C_s}{C_0}\right) + (C_s - C_0) = -\frac{\mu_m R_b C_b}{Y_s u} x \quad (5)$$

Suppose that the inlet concentration, C_0, equals 1000 mg/L, and the acceptable level of the contaminant's concentration, C_s, is 1 mg/L. The maximum specific growth rate, μ_m, the saturation constant, K_s, and the yield factor, Y_s, are estimated to be 5 d^{-1}, 50 mg/L, and 1 g cell/g substrate, respectively [8]. The flow rate of water, u, is taken to be 1×10^{-2} cm/s. Typically, the biomass concentration in surface soils is 10^8 cells/g soil corresponding to $C_b = 2 \times 10^{-4}$ g/cm^3. The retardation factor, R_b, is assumed to be 10. According to Equation 5, the width of the bio-wall required to reduce C_s from 1000 mg/L to 1 mg/L is 1.16 m. The exit concentration as well as the residence time

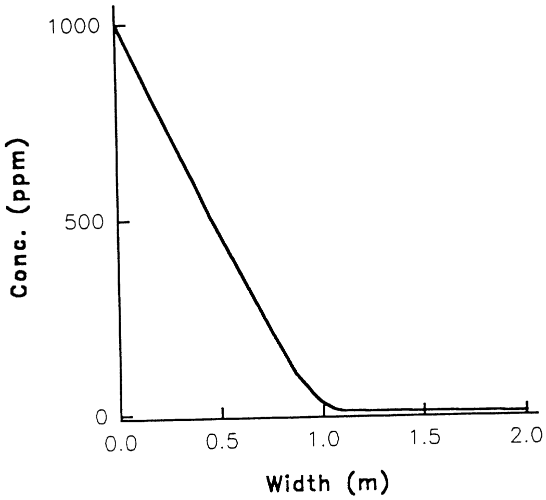

Figure 2. Contaminant concentration profile in the bio-wall.

of flow in terms of the width of the bio-wall are tabulated in Table 1; the corresponding concentration profile is plotted in Figure 2. A bio-wall, 2 m in width, can reduce C_s to 4×10^{-9} mg/L, thereby indicating that the contaminant is essentially completely destroyed within the bio-wall.

As an example, each individual component of BETX (benzene, ethyl-benzene, toluene and xylene, which are common constituents of petroleum fuels) is considered separately as a contaminant. The widths of the bio-wall necessary to reduce the contaminant concentration to various exit levels have been computed by considering that the inlet concentration is at the saturated aqueous concentration of the respective compound and that the other parameters remain invariant. The results are summarized in Table 2.

Alternative designs

The basic design of the bio-wall can be adapted for various situations. Some modified designs are outlined below.

Dual-trench system

If the pore structures of a soil provide surfaces and spaces sufficient for microbial growth, the soil itself serves as the packing of the bio-wall, thus giving rise to a dual-trench system, as illustrated in Figure 3. The pipes in the first trench, i.e., the inlet-flow trench, supply the main body of the system, i.e., the soil sandwiched between the two trenches, with oxygen, nutrients, genetically engineered microorganisms, and/or substrates for co-metabolic degradation. Excess biomass at the inlet of the main body may block transport of oxygen and nutrients by completely consuming them. It has been reported that injection of hydrogen peroxide is capable of removing this inlet microbial barrier and maintaining adequate biomass distribution [2].

Trickling filter system

Trickling filters are widely found in facilities for biological waste water treatment. Each trickling filter consists of a highly permeable medium, usually rocks of sizes ranging from 25 to 100 mm in diameter, to which microorganisms are attached and through which waste water is trickled or percolated. Figure 4 illustrates the bio-wall in which a trickling filter is incorporated. Water near

width of the bio-wall (m)	1	1.16	1.2	1.5	2.0
residence time of flow (hr)	2.8	3.2	3.3	4.2	5.6
exit contaminant conc. (ppm)	26	1	0.4	4×10^{-3}	4×10^{-9}

Table 1. Effect of the width of the bio-wall on the exit contaminant concentration for an inlet concentration of 1000 mg/L.

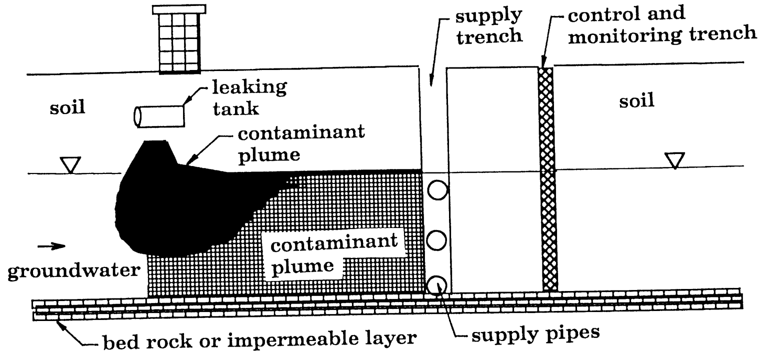

Figure 3. Dual-trench system.

the outlet of the bio-wall is extracted by a pump, conveyed to the top and sprayed; then, it trickles downward over the packings in the bio-wall. It is expected that the effectiveness of the technology will be greatly enhanced through incorporation of the trickling filter. Consequently, the width of the bio-wall can be substantially shortened, which, in turn, would reduce the construction cost under some circumstances.

Soil-flushing system

To accelerate the remediation, the bio-wall can be provided with soil-flushing capability. In this scenario, a pumping system is installed to recycle the effluent from the bio-wall as illustrated in Figure 5. The effluent is transported to the contaminated spot and spread onto an infiltration gallery to dissolve the contaminants. The hydraulic head created by the flushing will increase or even induce ground water flow that moves the contaminants into the bio-wall for transformation and detoxification.

DISCUSSION

The rate of biodegradation depends directly on the biomass concentration. Commonly, the biomass concentration, C_b, in soils deeper than 1 m is less than 10^4 cells/g soil (see, e.g., [9]). With this value and the parameter values given in Table 1, Equation 5

	inlet conc. (solubility) (ppm)	exit conc. (ppm)	width (m)	exit conc. (ppm)	width (m)	exit conc. (ppm)	width (m)
benzene	1780	1	2.11	0.1	2.29	$1x10^{-3}$	2.64
ethyl-benzene	152	1	0.16	0.1	0.18	$1x10^{-3}$	0.21
toluene	515	1	0.58	0.1	0.64	$1x10^{-3}$	0.74
m-xylene	175	1	0.19	0.1	0.21	$1x10^{-3}$	0.24
0-xylene	175	1	0.19	0.1	0.21	$1x10^{-3}$	0.24
p-xylene	198	1	0.22	0.1	0.24	$1x10^{-3}$	0.28

Table 2. Widths of the bio-wall necessary for treating BETX to various exit concentrations.

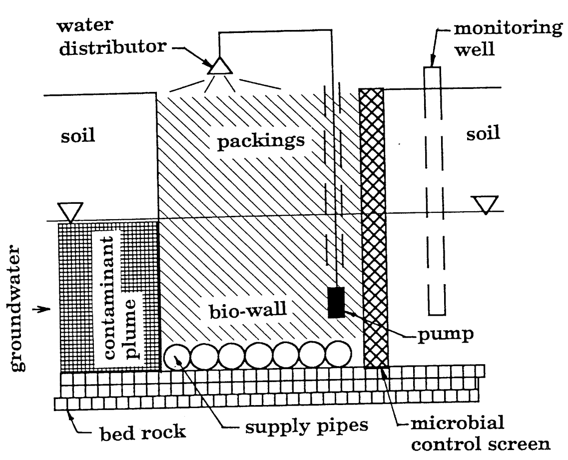

Figure 4. Bio-wall incorporated with a trickling filter.

yields x = 11.62 km, thereby indicating that the contaminant can migrate 11.62 km in ground water without a bio-wall. Nevertheless, this is too optimistic a value because some of the rate-limiting factors, such as the availability of oxygen and nutrients, have not been considered in the calculation. By taking into account the majority of the important rate-limiting factors, we obtain [10]

$$-r_i = \frac{\mu_{mi}}{Y_{si}} R_b C_b \left(\frac{C_{si}}{K_{si} + C_{si}}\right) \prod_j \left(\frac{C_j}{K_{sj} + C_j}\right) \qquad (6)$$

If the effects of all rate-limiting factors except the concentrations of biomass and contaminant are lumped into a factor assumed to be 0.5, the distance the contaminant travels without the bio-wall can be estimated to be 23.24 km, which is 20,000 times larger than the width of the bio-wall.

A bio-wall is constructed so that the most favorable environment for biodegradation is created and the concentrations of contaminants in the outlet stream are reduced to acceptable levels. The soil excavated to create a trench to accommodate the bio-wall is substantially less than the total amount of contaminated soil. The excavated soil is uncontaminated; therefore, it does not pose much difficulty for disposal. Moreover, a properly designed bio-wall renders it possible to circumvent the aboveground and underground structures or barriers.

Surfactants and genetically engineered microorganisms

Soils often form heterogeneous substructures such as aggregates and strata of different permeabilities. Heterogeneities frequently bring about uneven distribution of contaminants, which severely retards interphase mass transfer. Another factor that profoundly retards mass exchanges between phases is the exceedingly low solubilities of the contaminants. Mass transfer limitations prolong the time of remediation. Certain reactive agents, e.g., cosolvents or surfactants, have proved to be capable of enhancing mass transfer when injected into the contaminated soil [11]. Surfactants are highly regulated by EPA since no affordable technology is available which efficiently contains or collects all the surfactant-mobilized contaminants. As discussed above, a properly designed bio-wall can confine the contamination by destroying the contaminants that travel through it. Thus, the bio-wall is capable of preventing the migration of surfactant-mobilized contaminants and to make the application of surfactants beneficial.

To effectively biodegrade contaminants requires genetically-robust microorganisms. Genetically-engineered microorganisms (GEM's) may possess the capability of improving or even inducing biodegradation of some recalcitrant compounds. Currently, various GEM's are patented [12]; however, seeding GEM's is not encouraged by EPA because of possible micro-ecological catastrophes if GEM's are freely released into the environment. In contrast, a bio-wall is capable of manipulating and controlling microbial population and propagation. Water leaving the bio-wall is disinfected with the microbial control screen. The bio-wall, therefore, provides a controlled environment for GEM application.

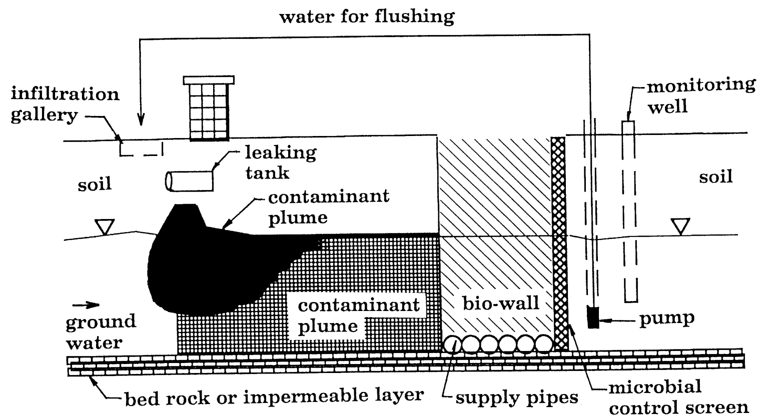

Figure 5. Soil-flushing system.

Emission control

Volatile organic contaminants (VOCs) will disperse into the air phase in a bio-wall and be transported out by air. To meet the air emission standards, air from the bio-wall must be collected for further treatment above ground. This can be accomplished by a system consisting of an impermeable cover spread over the bio-wall and a storage tank. The above-ground treatment of VOCs usually involves adsorption with granular activated carbon (GAC), chemical oxidation or incineration.

Soil vapor extraction (SVE) is a well-developed technology to treat VOC contamination in vadose zones. To maximize the extent of remediation, the bio-wall technology can be applied in conjunction with SVE. Since the vacuum in SVE creates a negative pressure head for the air phase, pumping air into the bio-wall may not be needed in this scenario. Air will be drawn into the bio-wall when one end of each oxygen-supply pipe is exposed to the atmosphere.

A rhizosphere may also be created by vegetation on the top of the bio-wall. The rhizosphere has the potential of playing the role of an in-situ bioreactor in the vadose zone to transform VOC's that pass through it [13]. The efficacy of vegetation to remediate an organically-contaminated site depends on both the plant species and the contaminants to be treated.

Prefabricated compartments and standardization

The optimum packing for specific contaminants remains a subject for further research. Once the optimum packing and arrangement of pipes are designed, the bio-wall can be prefabricated off-site in sections or compartments. Obviously, the design and construction of these compartments can be standardized for specific types of contaminants for cost reduction and convenience. After screening and characterizing a contaminated site, prefabricated compartments can be placed into the trench with ease.

Disposal

A bio-wall may be removed when the site is remediated. The normal procedure is to: (1) terminate the oxygen and nutrient supplies; (2) remove the pipes and microbe-control screen for reuse (or they may be simply left in place); and (3) recover or dispose of the packing without treatment since it is not hazardous. If GEM's are seeded, the bio-wall must be disinfected before disposal. This can be accomplished by injecting a disinfectant through the oxygen and nutrient supply pipes.

CONCLUDING REMARKS

An innovative technology, i.e., the bio-wall technology, is introduced for enhancing biodegradation in subsurface soils. This technology should enable us to confine spatial propagation of contaminants as well as microorganisms, and also to manipulate the physico-chemical conditions for accelerating bio-transformation. Various concepts, principles of design, and alternative designs of the bio-wall system have been elucidated. Through simulation, the system has been demonstrated to be effective; it can potentially reduce the contaminant plume-distance by several orders of magnitude. Further studies, especially laboratory experimentation and field demonstration, are required to determine the optimal design and to gather additional data for operation.

ACKNOWLEDGMENTS

Although the research described in this article has been funded in part by the United States Environmental Protection Agency under assistance agreements R-815709 and R-819653 to the Great Plains-Rocky Mountain Hazardous Substance Research Center for U.S. EPA Regions 7 and 8 with headquarters at Kansas State University, it has not been subjected to the Agency's peer and administrative review and, therefore, may not necessarily reflect the views of the Agency. No official endorsement should be inferred. This research was partially supported by the Kansas State University Center for Hazardous Substance Research.

NOMENCLATURE

a	interfacial area of the aqueous and solid phases per unit volume of the soil, L^2/L^3
C_b	concentration of biomass, M/L^3
C_j	concentration or intensity of rate-limiting substance except biomass and contaminant, M/L^3
C_s	aqueous concentration of the contaminant, M/L^3
C_{si}	aqueous concentration of the i-th contaminant compound, M/L^3
C_0	aqueous concentration of contaminant at the inlet, M/L^3
$\overline{\overline{E}}_{si}$	dispersive coefficient tensor for the i-th contaminant compound, L^2/t
$\overline{\overline{E}}_b$	dispersive coefficient tensor for biomass, L^2/t
k_d	decay rate constant, t^{-1}
K_{dsi}	partition coefficient of the i-th contaminant compound
K_s	saturation constant of the contaminant, M/L^3
K_{si}	saturation constant of the i-th contaminant compound, M/L^3
k_{si}	mass transfer coefficient of the i-th contaminant compound
K_{sj}	saturation constant of other rate-limiting substances, M/L^3
q_{si}	concentration of contaminant in the solid phase, M/L^3
R_b	retardation factor of biomass
r_i	reaction rate, $M/(L^3/t)$
t	time, t
u	mean pore-water velocity, L/t
$\overline{u}$	pore-water velocity vector, L/t
x	distance from the inlet in the bio-wall, L
Y_s	yield factor, M/M
Y_{si}	yield factor of the i-th contaminant compound, M/M
ε	void fraction
μ_m	maximum specific growth rate, t^{-1}

μ_{mi} maximum specific growth rate for biodegradation of the i-th contaminant compound, t^{-1}

ρ density, M/L^3

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