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ORIGINAL PAPER

Mercury resistance and volatilization by oil utilizing haloarchaea under hypersaline conditions

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Abstract The hydrocarbon utilizing haloarchaea, *Haloferax* (two strains), *Halobacterium* and *Halococcus* from a hypersaline coastal area of the Arabian Gulf, had the potential for resistance and volatilization of Hg^{2+}. Individual haloarchaea resisted up to between 100 and 200 ppm $HgCl_2$ in hydrocarbon free media with salinities between 1 and 4 M NaCl, but only up to between 20 and 30 ppm in a mineral medium containing 3 M NaCl, with 0.5% (w/v) crude oil, as a sole source of carbon and energy. *Halococcus* and *Halobacterium* volatilized more mercury than *Haloferax*. The individual haloarchaea consumed more crude oil in the presence of 3 M NaCl than in the presence of 2 M NaCl. At both salinities, increasing the $HgCl_2$ concentration in the medium from 0 to 20 ppm resulted in decreasing the oil consumption values by the individual haloarchaea. However, satisfactory oil consumption still occurred in the presence of 10 ppm $HgCl_2$. It was concluded that haloarchaea with the combined potential for mercury resistance and volatilization and hydrocarbon consumption could be useful in removing toxic mercury forms effectively from oil free, mercury contaminated, hypersaline environments, and mercury and oil, albeit less effectively, from oily hypersaline environments.

Keywords Crude oil · Extreme salinity · Haloarchaea · Mercury resistance · Mercury volatilization

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Introduction

Industrial wastes containing many 100 million tons of organic and inorganic mercury compounds (Pahan et al. 1995) globally pollute the biosphere, and oil-contaminated areas are usually simultaneously contaminated with heavy metals including mercury (Barringer et al. 2005, 2006; Wiatrowski et al. 2006; Baker-Austin et al. 2007). Mercury is used in the production of gold, vaccines, antimicrobials, amalgams and electronics (Schelert et al. 2004). There are reports on indigenous soil and aquatic bacteria that biodegrade oil (for reviews see Rosenberg 2006; Radwan 2008), and others that resist and volatilize mercury in oil free environments (Chiu et al. 2007; for reviews see references Silver and Phung 1996; Osborn et al. 1997; Nies 1999; Barkay et al. 2003).

Mercury detoxification is performed via the sequential action of two plasmid-encoded enzymes: organomercurial lyase and Hg^{2+} reductase (mer) system (Pahan et al. 1995; Schelert et al. 2004). The lyase breaks the carbon-mercury covalent linkage producing Hg^{2+} which is reduced by the mer system to the less toxic and more volatile Hg^0, as early recognized by Summer and Silver (1978). The two enzymes require (–SH) compounds and FAD stimulates their activities (Schottel 1978; Pahan et al. 1990). Cysteine was also detected at the C-terminal end of Tn 501 Hg^{2+} reductase (Moore et al. 1992). Literature reports indicate that most of these studies used gram-negative bacteria, but also few gram-positive bacteria contain the mercury detoxifying enzymes (Moore et al. 1989; Wang et al. 1989; Pahan et al. 1991). Little is known about mercury detoxifying enzymes in archaea (Schelert et al. 2004).

Many of the mercury-resistant bacteria isolated from pristine environments, e.g., *Acinetobacter, Alteromonas, Bacillus, Mycobacterium, Pseudoalteromonas, Pseudomonas*

and *Rhodococcus* are known for their hydrocarbon utilization potential. Recently, a report has been published on 18 different indigenous bacteria with the combined potential for oil utilization and mercury volatilization in conventional (not hypersaline) coastal areas (Sorkhoh et al. 2010). Obviously such bacteria have the potential for cleaning conventional oil and mercury contaminated areas degrading the oil and detoxifying Hg^{2+}. Contaminated hypersaline areas, on the other hand have not been studied adequately (Lefebvre and Moletta 2006), and their cleaning does not seem to be possible with "non-extremophilic" microorganisms (Pieper and Reineke 2000; Oren 2002). This allows to assume haloarchaea as the potential alternative microorganisms in these applications, even though they could be metabolically less diverse than bacteria (Oren et al. 1992). Evidence is accumulating that some archaea have the potential for hydrocarbon biodegradation (Bertrand et al. 1990; Kulichevskaya et al. 1992; Riis et al. 2003; Al-Mailem et al. 2010; Tapilatu et al. 2010), and that some, albeit very few, resist heavy metals including mercury (Wang et al. 2004; Baker-Austin et al. 2007).

The major objectives of this paper were to study the mercury resistance and volatilization potential of four hydrocarbon utilizing archaeal strains isolated from a hypersaline soil (Al-Mailem et al. 2010), and to investigate the mutual effects of oil and mercury concentrations on the removal of these pollutants in haloarchaeal cultures containing extremely high sodium chloride concentrations.

Materials and methods

The haloarchaeal strains

Haloferax sp. HA1, *Haloferax* sp. HA2, *Halobacterium* sp. HA3 and *Halococcus* sp. HA4 were used in this study. The four haloarchaeal strains were originally isolated from a hypersaline (>4 M NaCl) coastal area of the Arabian Gulf, the so-called super-tidal sabkha of the southern (Khiran) coast of Kuwait. The isolation procedure and the identification of the strains by sequencing their 16S rRNA genes have been described thoroughly in a previous publication (Al-Mailem et al. 2010). Cell numbers in liquid cultures were counted microscopically using hemocytometers.

Mercury resistance and volatilization

Inorganic mercury in the form of $HgCl_2$ was used, and three parallel replicates were done for each analysis. To determine the highest $HgCl_2$ concentration tolerable by the individual haloarchaea, a loopful of a cell suspension (one loopful of a 3 days biomass in 5 ml sterile 1 M NaCl solution) of the tested strain was streaked on nutrient agar medium aliquots with increasing concentrations of $HgCl_2$ from 0 to 300 ppm and NaCl, from 0 to 4 M (See the "Results" following, Table 1). Streaking was also done on a solid mineral medium (Mevarech and Werczberger 1985) supplemented with 0.5% (w/v) crude oil (Kuwaiti light crude) as sole source of carbon and energy, and 3 M NaCl. Cultures were incubated in the dark at the optimum temperatures, 40°C for *Haloferax* and 45°C for *Halobacterium* and *Halococcus* (Al-Mailem et al. 2010) for 10 days and examined daily for growth.

To determine the $HgCl_2$ concentrations in cells and culture metabolites (Han et al. 2006), these materials were digested with concentrated HNO_3 and HCl, 2:1, v/v, on a hot plate. The digested solutions were filtered, diluted with 1% HNO_3 and total mercury concentrations were measured by an inductively coupled plasma-atomic emission spectrophotometer (ICP-AES; Thermo Elemental, Franklilakes, NJ, USA, or JY 2000 Ultrace, Jobin–Yvon Horiba) using a certified reference soil standard containing mercury solution. Reportedly, this method should produce an average

Table 1 Effects of crude oil and salinity of the culture medium on mercury resistance by the four haloarchaea studied

$HgCl_2$ concentration (ppm)	*Haloferax* sp. HA1 on						*Haloferax* sp. HA2 on						*Halobacterium* sp. HA3 on						*Halococcus* sp. HA4 on					
	Nutrient agar with NaCl (M)					Oil medium with 3 M NaCl	Nutrient agar with NaCl (M)					Oil medium with 3 M NaCl	Nutrient agar with NaCl (M)					Oil medium with 3 M NaCl	Nutrient agar with NaCl (M)					Oil medium with 3 M NaCl
	0	1	2	3	4		0	1	2	3	4		0	1	2	3	4		0	1	2	3	4	
0	−	+	+	+	+	+	−	+	+	+	+	+	−	+	+	+	+	+	−	+	+	+	+	+
10	−	+	+	+	+	+	−	+	+	+	+	+	−	+	+	+	+	+	−	+	+	+	+	+
20	−	+	+	+	+	+	−	+	+	+	+	+	−	+	+	+	+	+	−	+	+	+	+	+
30	−	+	+	+	+	−	−	+	+	+	+	−	−	+	+	+	+	+	−	+	+	+	+	−
50	−	+	+	+	+	−	−	+	+	+	+	−	−	+	+	+	+	+	−	+	+	+	+	−
100	−	−	+	+	+	−	−	+	+	+	−	−	−	−	+	+	+	−	−	+	+	+	+	−
200	−	−	−	+	−	−	−	−	−	−	−	−	−	−	−	+	−	−	−	−	−	−	−	−
300	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−

+ positive growth, − no growth

mercury recovery of 100% with a 0.92% relative error (Han et al. 2006).

Mercury volatilization by the individual isolates was measured as described by Barkay (1987). Three-days-old archaeal biomass, 0.5 g, was suspended in 100 ml nutrient broth supplemented with 100 ppm mercury as $HgCl_2$ and 3 M NaCl, and shaken at 120 rpm at 40°C for *Haloferax* and 45°C for *Halobacterium* and *Haloccous* for 8 days, in the dark. Suspension, 5 ml samples were taken at time 0 and in 2 days intervals and centrifuged at 6,000 RCF for 10 min at 4°C. The wet biomass and supernatant as well as 1 ml of the control cell-free medium containing $HgCl_2$ standard solution (50 ppm) were digested and the residual mercury was determined by ICP-AES as mentioned above. The percent of mercury remaining in the medium was calculated.

Oil consumption

Liquid mineral medium (Mevarech and Werczberger 1985; organic constituents deleted and 0.1% KNO_3 added as a nitrogen source) aliquots, 200 ml were dispensed in 500 ml conical flasks, and provided with 0.5%, w/v, crude oil. To study the effect of salinity, in one series of flasks the medium salinity was adjusted to 2 M and in the other series to 3 M NaCl. Each flask was inoculated with a volume of a common inoculum (one loopful of 3 days old culture in 5 ml sterile 3 M NaCl solution) containing 5×10^3 cells ml^{-1}, and sealed. Three replicates were prepared throughout. Incubation was done in the dark with shaking at 120 rpm at 42°C. Cultures were harvested after 3 weeks, cell numbers were counted microscopically and the residual oil was recovered with three successive portions of 15 ml pentane, the combined extract completed to 50 ml with pentane, and 1 µl was analyzed by gas liquid chromatography (GLC). Hydrocarbon consumption was expressed in terms of percentage total peak area reduction based on the peak areas of the controls (similarly prepared, but subjected to autoclaving to kill the cells). GLC was done using a Chrompack (NJ, USA) CP-9000 instrument equipped with a FID, a WCOT fused silica CP-Sil capillary column, and a temperature program of 45–310°C, raising the temperature 10°C min^{-1}.

Results and discussion

Evidence for the biodegradation of crude oil and pure hydrocarbons by the four haloarchaeal strains has been documented in a recent publication (Al-Mailem et al. 2010). The results in Table 1 show that the four haloarchaeal strains could resist up to between 100 and 200 ppm $HgCl_2$ in a hydrocarbon free medium. This mercury resistance level was valid at all medium salinities, between 1 and 4 M. As expected, in the absence of NaCl none of the four haloarchaea could grow. For comparsion, hydrocarbon utilizing, mercury resistant non-extremophilic bacteria viz., *Gordonia alkanivorax*, *Vibrio tasmaniensis*, *Alcanivorax barkumensis*, *Bacillus ashii*, *Marinobacter hydrocarbonoclasticus* and *Psychrobacter celer* from a pristine coastal area of the Arabian Gulf could resist also in hydrocarbon free media up to between 50 and 100 ppm $HgCl_2$ (Sorkhoh et al. 2010). In other words, the haloarchaeal strains growing at extreme salinity levels resisted $HgCl_2$ concentrations similar to or even higher than those resisted by marine bacteria growing in the presence of only 0.5 M NaCl, the normal salinity of seawater.

Table 1 shows further that in the presence of 0.5% crude oil as a sole source of carbon and energy, the four haloarchaea could still resist, but lower concentrations of $HgCl_2$, namely up to only between 20 and 30 ppm. In comparison, four of the non-extremophilic coastal bacteria listed above resisted up to only 10 ppm $HgCl_2$ and two of them failed to grow in the presence of even only 1 ppm $HgCl_2$ (Sorkhoh et al. 2010). This latter result too demonstrates that the haloarchaea resist similar or higher levels of mercury in the presence of hydrocarbons than those resisted by coastal non-extremophilic bacteria. In this context, most of the studies in the literature on mercury resistance by bacteria used HgCl concentrations of only 10–20 ppm. However, the results recorded above should be considered in view of the effects of mercury speciation in the nutrient media on its bioavailability and toxicity (Ramamoorthy and Kushner 1975), and of that chloride readily complexes with Hg^{2+} in various forms depending on the relative concentrations, leading to different toxicities (Hahne and Kroontje 1973; Barkay et al. 1997). Therefore, a part of the mercury resistance recorded here could be due to this speciation. Mercury speciation models showed that as Cl increases in the absence of sulfides, Hg^{2+} speciates as negatively charged forms of $HgCl_3$ (−1) and $HgCl_4$ (−2) (Barkay et al. 1997), which are less bioavailable and toxic (Barkay et al. 2003; Crespo-Medina et al. 2009).

Figure 1 illustrates the kinetics of mercury volatilization by the individual haloarchaea in the presence of 3 M NaCl. Autoclaved *Halococcus* cells (control) failed to volatilize any mercury, whereas fresh cells of the individual haloarchaea volatilized between about 40 and 65% of the available mercury after 8 days. In this context, Barkay (1987) reported that non-extremophilic bacteria volatilize most of the mercury rather quickly. As already mentioned mercury volatilization by bacteria involves the reduction of Hg^{2+} via the mer system to Hg^0, which is volatile and less toxic (Summer and Silver 1978). While the mer system has been extensively studied in bacteria, little is known about archaea (Schelert et al. 2004), although mer gene homologs

were recently detected in several archaeal strains among them haloarchaea (Barkay et al. 2010).

It is interesting from the basic and practical viewpoints that haloarchaea are at least as efficient as bacteria in mercury resistance and volatilization. According to the very few relevant reports in the available literature, *Sulfolobus solfataricum* can resist mercury (Schelert et al. 2004), and *Halobacterium* sp. (Wang et al. 2004) and *Ferroplasma acidarmanus* (Baker-Austin et al. 2007) can resist arsenic. Our results are thus among the few showing that haloarchaea which dominate in highly saline environments, removed mercury from the growth media showing a potential for activities in contaminated environments. Microbiological mercury removal from soil, whether by bacteria or archaea is obviously associated with atmospheric mercury pollution, even though Hg^0 is less toxic than Hg^{2+}. The results of this study imply that the four strains described with their ability to eliminate Hg^{2+} from the growth medium, may be good candidates for further studies on mer functions in archaea, particularly haloarchaea.

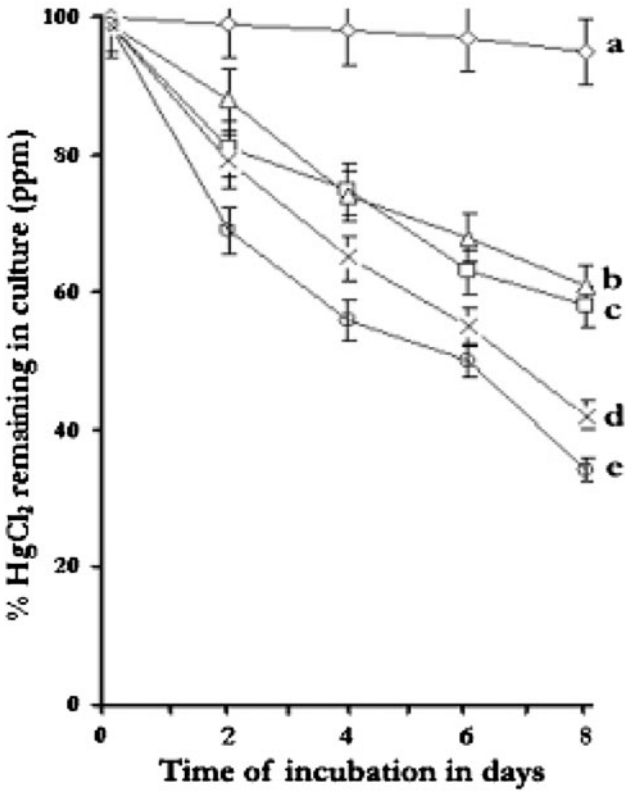

Fig. 1 Kinetics of mercury volatilization in haloarchaeal cultures containing initially 100 ppm $HgCl_2$ and 3 M NaCl. *a* Autoclaved *Halococcus* (Control), *b Haloferax* sp. HA2, *c Haloferax* sp. HA1, *d Halobacterium* sp. HA3, *e Halococcus* sp. HA4

The quantitative measurements of mercury volatilization showed that out of the 100 ppm mercury added into each culture medium as $HgCl_2$, 42.6 ± 1.8, 46.2 ± 1.4, 50.8 ± 1.8 and 51.6 ± 2.4 ppm were volatilized by *Haloferax* sp. HA1, *Haloferax* sp. HA2, *Halobacterium* sp. HA3 and *Halococcus* sp. HA4, respectively. The corresponding values for mercury retained in the media were, respectively, 57 ± 0.8, 53.6 ± 1, 48.6 ± 0.8 and 47.8 ± 0.4 ppm, and for mercury bound by the cells 0.32 ± 0.02, 0.22 ± 0.02, 0.56 ± 0.02 and 0.52 ± 0.02.

Confirming our earlier report (Al-Mailem et al. 2010), the results in Table 2 show that the crude oil consumption values by the four haloarchaea were higher at 3 M than at 2 M NaCl concentrations in the medium. This was true irrespective of the amount of $HgCl_2$ added to the medium. On the other hand, gradually increasing the $HgCl_2$ concentration in the medium from 0 to 20 ppm resulted in gradual inhibition of crude oil consumption at both salinities (see also Fig. 2). However, substantial rates of oil consumption still occurred in the presence of up to 10 ppm $HgCl_2$. The cell numbers of *Halococcus* (the most efficient of the four strains in mercury volatilization; see Fig. 1) in mercury free medium after 2 weeks was 1.9×10^8 cells ml^{-1}. The corresponding numbers in media containing 5, 10, 15 and 20 ppm mercury as $HgCl_2$ were 3.2×10^7, 5.7×10^6 and 1.5×10^5 cells ml^{-1}, respectively.

It has been known for a long time that mercury inhibits hydrocarbon consumption by bacteria (Walker and Colwell 1976). Recent studies confirmed and consolidated this

Table 2 Effect of mercury concentration on the oil-attenuation potential of archaeal isolates

$HgCl_2$ concentration (ppm)	% Crude oil consumption by							
	Haloferax sp. HA1		*Haloferax* sp. HA2		*Halobacterium* sp. HA3		*Halococcus* sp. HA4	
	2 M NaCl	3 M NaCl	2 M NaCl	3 M NaCl	2 M NaCl	3 M NaCl	2 M NaCl	3 M NaCl
0 (Control)	64 ± 3.1	73 ± 3.5	55 ± 2.7	71 ± 3.5	55 ± 2.6	82 ± 4.0	59 ± 2.8	72 ± 3.5
5	57 ± 2.7	70 ± 3.2	46 ± 2.2	67 ± 3.2	47 ± 2.2	73 ± 3.5	55 ± 2.6	70 ± 3.1
10	45 ± 2.1	62 ± 3.0	31 ± 1.4	57 ± 2.7	46 ± 2.2	70 ± 3.4	53 ± 2.1	65 ± 3.1
15	41 ± 1.9	54 ± 2.6	27 ± 1.2	53 ± 2.5	38 ± 1.8	61 ± 3.0	46 ± 2.1	52 ± 2.1
20	26 ± 1.2	42 ± 2.0	22 ± 1.0	39 ± 1.7	29 ± 1.3	48 ± 2.3	29 ± 1.3	43 ± 1.9

Values are means of three replicates each, ± standard deviation. Incubation was for 3 weeks

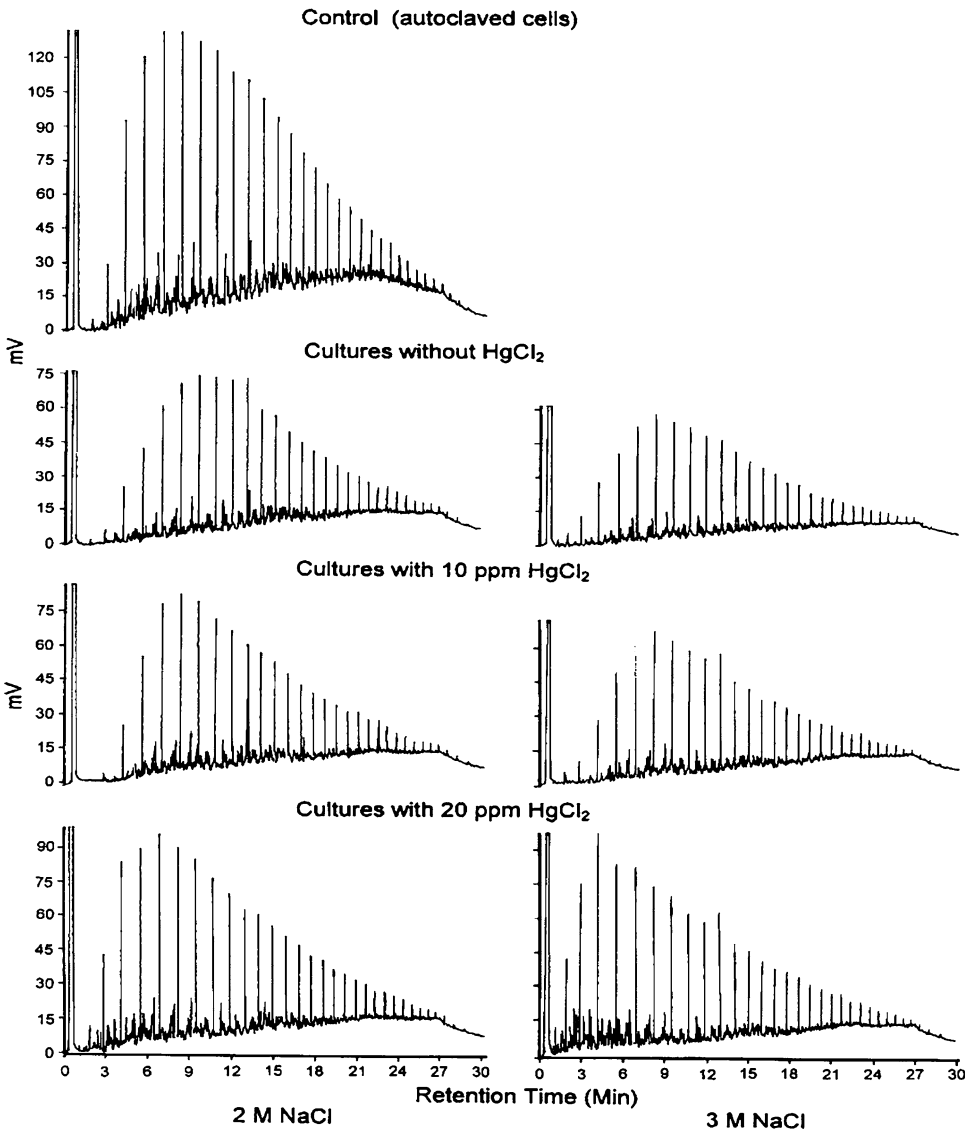

Fig. 2 Typical GLC profiles of residual crude oil hydrocarbons in media that had supported *Halococcus* HA4. Note that the hydrocarbon peaks were generally smaller in cultures with 3 M NaCl than with 2 M NaCl, indicating better oil consumption at 3 M than at 2 M NaCl. At both salinities the smallest peaks were those recovered from $HgCl_2$ free cultures; with 20 ppm $HgCl_2$ the peaks were larger than with 10 ppm $HgCl_2$ which reflects the inhibitory effect of mercury on hydrocarbon consumption by the haloarchaeon

conclusion (Sorkhoh et al. 2010), and this study shows for the first time that such inhibition occurred also with the haloarchaea, a result which demonstrates a metabolic similarity between representatives of the bacterial and archaeal domains.

In conclusion, hypersaline environments harbor haloarchaea with the combined potential for oil consumption and mercury resistance and volatilization. These extremophiles could be useful biological systems for removing toxic forms of mercury effectively from mercury contaminated, non-oily, hypersaline areas, and oil and mercury relatively slowly from hypersaline areas moderately contaminated with oil and mercury. In practice, too heavily polluted soils may be mixed with pristine soil, thus reducing the oil and mercury concentrations to the levels tolerated by the microorganisms. With progressive bioremediation the concentrations of these pollutants would steadily decrease to levels below the critical inhibitory concentration. By then, the process would proceed at a satisfactory rate. The volatilized Hg^0, would still remain as a less toxic (than Hg^{2+}) atmospheric pollutant, that can potentially reach soil and surface waters by precipitation.

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