

On-site mercury-contaminated soils remediation by using thermal desorption technology

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Abstract

In this study, the thermal desorption process was used to treat a mercury-contaminated soils in Taipei. A series of bench or pilot plant experiments were also performed the optimized operation condition. The results showed that the concentrations of residual mercury in all treated soils were below 2 mg/kg, some even lower than 0.05 mg/kg. The supernatant and exhaust gas stream of the condensed desorbed mercury vapor in the remediation site were also met with the effluent standard. The total fee was estimated to be US\$ 3,557,000, when treating contaminated soil leading to a unit treatment cost of US\$ 834/m³ of soil.

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1. Introduction

Mercury, which is on the priority list of 129 chemical substances by USEPA, is one of the most toxic chemicals in earth. In many cases, it was found that the sump leakage or inappropriate waste dumping during the early stages of industrialization resulted in mercury contamination in soil [1]. Over the last decade, injuries by mercury toxicity have been observed at Minamata and Nigata of Japan, Iraq, Pakistan and New Mexico of United States [2]. In Taiwan, spills, leaks and accidental discharges of mercury containing chemicals have contaminated soil at several sites. Human beings have been found to be harmed throughout the accumulation of organic- or inorganic-mercury in many different routes, which causing a significant influence on human health.

Mercury exists in soil mostly with mercuric status and its mobility was influenced by the physical- and chemical-adsorption ability of soil. Physical adsorption is caused by

van der Waals force while chemical-adsorption occurs via chemical reaction between adsorbent and the adsorbate. In addition, the adsorption ability is also influenced by the particle size, composition, organic content and surface characteristics of the soil. Generally, the mercury exists in the soil only as in the form of element state or as mercury(II) compounds, such as HgS, HgO and HgCO₃. When a temperature reaches to 600–800 °C, these mercury compounds would be converted into gaseous mercury and the mercury could be purified and recovered.

Some treatment processes, such as stabilization/solidification, thermal desorption, in situ vitrification, soil flushing and soil washing, could be used for mercury-contaminated soil remediation [3]. In recent years, the thermal desorption treatment, a kind of ex situ remedial technology which converts mercurial compounds into the volatile mercury, has been considered as a preferred treatment technology for mercury-contaminated soils remediation, due to the advantages of more safety, less emission of treating substance and less energy consuming as compared with other process [4,5]. Middle-range temperature (540–650 °C) of thermal desorption can decrease the concentration of the residual mercury to a lower level below 2 mg/kg and the

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mercury can be reclaimed with a purity of 99% for sale despite of its different structures and forms [4–7].

In order to solve the mercury-polluted soil problem, this study using on-site thermal desorption remediation process to treat the mercury-contaminated soils in the southern area of Taipei. A series bench, pilot plant and full-scale experiments were performed to optimize and evaluate the mercury removal efficiency. The cost analysis of the full-scale process was also performed in this study.

2. Materials and method

2.1. Site background

The mercury-polluted site, which was contaminated by an alkali chlorine factory, is located in the south of Taipei with an area of about 3 ha. The factory started to operate since 1944 and closed in 1985 lasting for 41 years. During this period, condensed sodium chloride solvent was electrolyzed by diaphragm- and mercury electrode-electrolysis to produce alkali chlorine, liquid chlorine and sodium hydroxide. Before 1965, only diaphragm electrolysis was used to produce alkali chlorine and approximately 600 t sludge containing mercury was accumulated. Since 1965, mercury electrode electrolysis was added to produce liquid chlorine and sodium hydroxide, which electrolyzed sodium chlorine with mercury as the cathode and graphite or titanium as the anode. In the electrolysis process, the clear sodium chlorine solution constantly flowed into the electrolyte bath and the settled mercury sludge was sent through filter device. Then, the solid filtration portion was solidified by solidification process and the liquid portion flowed back to electrolyte bath for further electrolysis. The layout of factory buildings is shown in Fig. 1. The west area was used for production and the east area was for storage of raw materials, products and electrical machinery.

In order to understand which part of the site is mercury-polluted area, 20 soil samples, numbered from L-1 to L-20, were sampled and the mercury concentration was examined. The locations of the sample sites are shown in Fig. 2 and the mercury concentrations were further discussed in Section 3.2.1. The distribution of the mercury concentration site was simulated with Kriging method [8], which is an optimal prediction method designed for geophysical variables with a continuous distribution and the treatment area for full-scale thermal desorption process was further decided and marked up as (A–F) as shown in Fig. 2.

2.2. Pilot plant test

The pilot plant tests were carried out to evaluate the parameters for the subsequent on-site thermal desorption remediation by using pure mercury as polluted chemical reagent. The maximum mass capacity of the pilot plant was 0.2 t/day. In order to prevent the secondary pollution from air and condensed water, a post-treatment process was set to

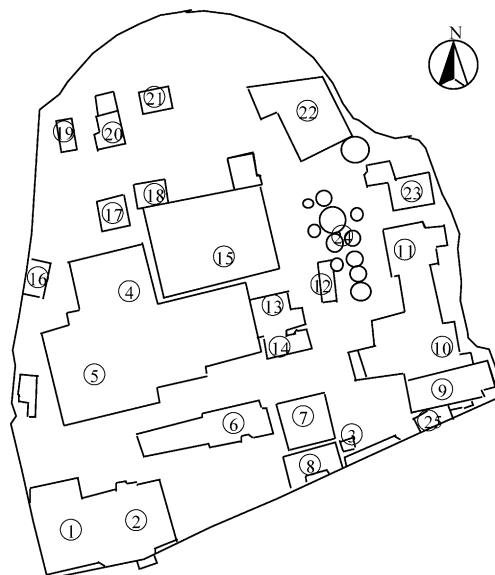


Fig. 1. Layout of the factory buildings: (1) storage tank 1; (2) workroom; (3) platform scale; (4) electrolytic room C; (5) electrolytic room ABC; (6) storage tank 2; (7) office; (8) transformer station; (9) storage tank 3; (10) NaCl storeroom; (11) steam boiler; (12) a work bench; (13) electric power control room; (14) NaCl settling tank; (15) mercury tank; (16) storage tank 4; (17) lime room; (18) by-product of HCl storeroom; (19) storage tank 5; (20) by-product of sodium hypochlorite room; (21) water chamber; (22) liquid room; (23) SO₂ gas product; (24) products storeroom; (25) guard room.

minimize the mercury concentration, which was numbered as 1a–c as showed in Table 1. Additionally, a pilot scale pretest, as numbered as 1d, is also necessary to design the full-scale plant. The mercury vapor yield test 1a was designed to understand how many mercury could be generate by different air suction flow rate and this data would be further used in the breakthrough curve test 1b. The experiment 1b was designed to realize the adsorption performance of activated carbon, which would be further used in the sulfur-impregnated

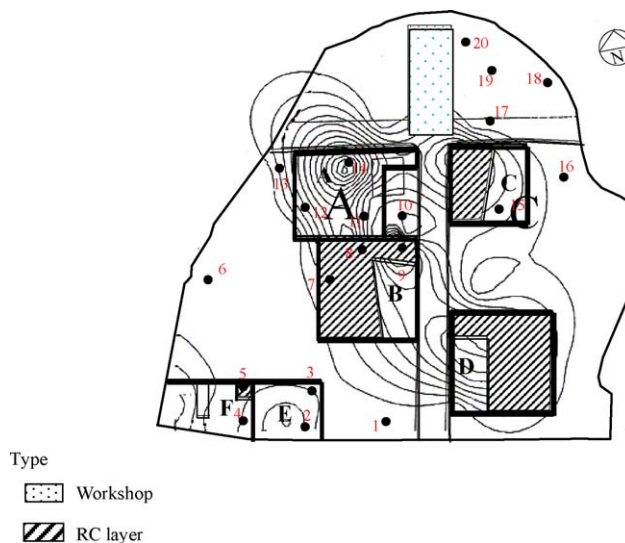
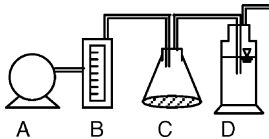
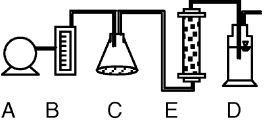
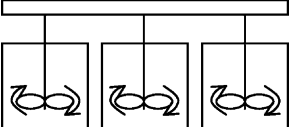
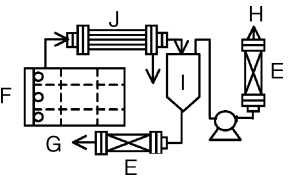


Fig. 2. Sampling site and treatment area.

Table 1
Experimental process and apparatus used for this research

Test	Item	Purpose	Equipment	Procedure
1a	Mercury vapor yield test	Basic measurement for breakthrough test		<ol style="list-style-type: none"> 1. Put pure mercury in the conical flask and take a certain quantity of absorbed liquid into the impinger 2. Turn on the air pump and fix the flow rate 3. Change the aspiration time. Measure mercury concentration in the absorbed liquid
1b	Breakthrough curve test	To understand the breakthrough time of air and wastewater by adsorbent in the thermal desorption test		<ol style="list-style-type: none"> 1. Take a certain quantity of absorbed liquid into the impinger and turn on air pump to absorb the mercury passing through packed adsorbent inside the column 2. Turn off the air pump for each interval and change the impinger 3. Measure mercury concentration in the absorbed liquid 4. Let the accumulated amount of passing through as x-axis, the outlet concentration as y-axis. Then, the breakthrough curve of adsorption can be obtained
1c	Condensed water coagulation test	Using jar test to determine the required dose		<ol style="list-style-type: none"> 1. Take the pure mercury into the beaker and adjust the pH between 7 and 8 2. Add the mix of metal scavengers and calcium hydroxide in different ratios 3. Stir 2–3 min and then add polyaluminum chloride as coagulant aids 4. Let the sample settle for 30 min and analyze the mercury content of the supernatant
1d	Thermal desorption test	Optimizing the best temperature and retention time of thermal desorption		<ol style="list-style-type: none"> 1. Take the contaminated soil and place it on the tray. Then, place the tray into electric heater 2. Set the final temperature and retention time with the electric heater 3. Analyze mercury concentration of the soil by sampling after cooling down the electric heater to room temperature 4. Take the aqueous samples in the outlet of the condensation water and air adsorbent tube and analyze mercury concentration

Note: (A) pump; (B) flow meter; (C) pure mercury flask; (D) impinger; (E) activated carbon adsorption column; (F) thermal desorption kiln; (G) the outlet of the condensation water adsorbent tube; (H) the outlet of the air adsorbent tube; (I) collect tank; (J) condenser.

activated carbon adsorption tank. The experiment devices and procedure used in pilot plant study are shown in Table 1.

2.3. On-site process and equipment

Two types of on-site process, pretest and full-scale remediation test were carried out in this study. The pretest was performed to optimize the reaction temperature and time of the full-scale thermal desorption process.

2.3.1. On-site pretest experiments

The purpose of pretest experiments is to optimize the operated time and temperature of full-scale thermal desorption process. For pretest experiment, the mercury-contaminated soil was excavated 1.8 m deep underground with an area of about 6 m × 6 m to a total volume of 49 m³ of mercury-polluted soil, which was carried out by dumping truck for further weighing, recording and storage. The mercury-polluted soil was used in 12 pretest experiments to perform the optimized the operation time and temperature. The operated time and temperature was controlled as 650 °C for 3 h followed by 700 °C for 2 h (2a), 750 °C for 2 h (2b), 650 °C for 2 h followed by 600 °C for 3 h (2c), 750 °C for 2 h (2d) and 750 °C for 3 h (2e), respectively.

2.3.2. Full-scale on-site remediation test

According to the optimized result of on-site pretest experiments, the remediation efficiency of the mercury-contaminated soil by thermal desorption technology were performed in this study. From the simulation result of Kriging method, the treatment area for full-scale thermal desorption process is located as (A–F) and the total remediation area and soil volume were 3746 and 4174 m³, respectively, as shown in Fig. 2 and Table 2.

Fig. 3 showed the schematic diagram of the full-scale thermal desorption plant. In each experiment, 2 t of the mercury-contaminated soil was treated. Firstly, the polluted crushed soil was placed on a tray and then transferred onto a platform truck, which would be subsequent put into the kiln (part 1 in Fig. 3) for thermal desorption. After being treated by thermal desorption, the soil was cooled by spray water and returned back to the site. The exhausted mercury vapor was cooled down in the cooling water recycle system (part 2) and further condensed in the condensation water separate tank (part 3) and

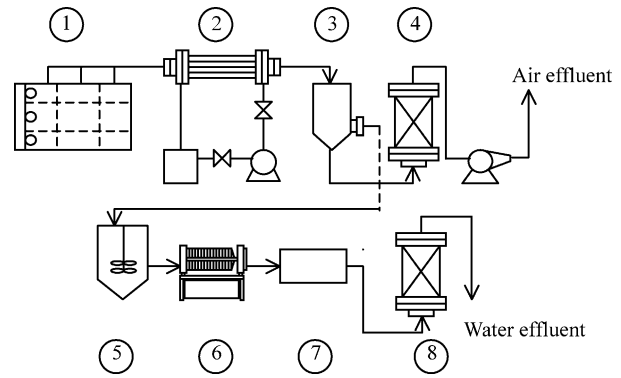


Fig. 3. On-site thermal desorption system process flow diagram: (1) thermal desorption kiln; (2) cooling water recycle system; (3) condensation water separate tank; (4) sulfur-impregnated activated carbon adsorption tank; (5) coagulation tank; (6) dewatering device; (7) buffer tank; (8) sulfur-impregnated activated carbon adsorption tank.

tank (part 3). The gas with few mercury flowed into the sulfur-impregnated activated carbon adsorption tank (part 4) to adsorb the residual mercury followed by emission to the air. The condensed water was further coagulated with metal scavengers, calcium hydroxide and polyaluminum chloride in coagulation tank (part 5) and dewatered the sludge in dewatering device (part 6). The supernatant of the mercury-contained water flowed through the buffer tank (part 7) and into the sulfur-impregnated activated carbon adsorption tank (part 8) to adsorb the mercury in the condensed water and followed by emission in the effluent.

The thermal desorption process used in this study was easy operation, convenient maintenance and small yield of exhaust gas. It can effectively decrease the treatment cost to achieve the aim of thermal treatment. The final theoretical temperature inside the kiln was 650 °C, but 650–800 °C was adopted in this study to ensure the mercury concentration in the soil reducing below 2 mg/kg. In the process, vacuum pump was used to keep the thermal desorption kiln and the connecting pipes in a negative pressure condition. The efficiency of the thermal desorption treatment, the performance of the pollution prevention and the cost and effectiveness of the on-site works were evaluated in this research.

2.3.2.1. Thermal desorption oven. Two sets of thermal desorption kiln, each was 2.97 m long with a net inner volume (deducting fireproof brick) of 3.5 m³, was used in the full-scale remediation process. In each treatment, 2 t of the mercury-contaminated soil was fed into each kiln. The maximum mass capacity of each kiln was 8 t/day. Thus, 16 t of contaminated soil could be treated in the process every day. The kiln was made of stainless steel boards. The size of each steel board is 0.99 m long and 0.66 m wide. Electric welding soldered the steel boards' junctures and the seam of steel boards inside the stove was coated by fireproof mud to ensure the gas tightness of the kiln.

Table 2
The remediation area and volume of on-site thermal desorption

Location	Remediation area (m ²)	Average depth (m)	Remediation volume (m ³)
A	872	2	1482
B	547	2	985
C	269	1	269
D	537	1	483
E	550	1	275
F	971	1	680
Total	3746	–	4174

Table 3
Functions of thermal desorption device

Equipment item	Function	Device
Thermal desorption oven	Contaminated soils desorbed by high temperature vacuum heating	Output power 300 kW, source of electricity 3Ø380 V, three-stage SCR temperature respond, L2970 mm × W 1650 mm × H2260 mm
Platform truck	Feeding devices	L2700 mm × W1150 mm × H410 mm
Tray	Laid for mercury-contaminated soils	L2650 mm × W920 mm × H215 mm × T3, stainless steel (SUS310)
Condenser	Cooling of high temperature gas	L2712 × Ø267, SUS316L, L860 × Ø12, stainless steel (SUS316)
Condensation water tank	Separating condensed water from gas, collecting mercury crystal or compound	H1619 mm × Ø1300 mm
Vacuum pump	Keeping the negative pressure status in the thermal desorption oven	5 Hp, 3Ø380 V
Sulfur-impregnated activated carbon tank	Removal of mercury stream in air and water	H1250 mm × Ø300 mm

2.3.2.2. *Tray*. The tray was 2.65 m long, 0.92 m wide and 0.215 m high. The flange of the tray was 0.1 m high and the maximum capacity for the soil was 0.25 m³. Eight trays were used in each treatment. Due to the high temperature performance between 650 and 850 °C, the material of the tray was designed to prevent high temperature, alkali and acid attack.

2.3.2.3. *Platform truck*. The platform truck was 2.7 m long, 1.15 m wide and 0.41 m high. Fireproof bricks were paved on it to prevent the heat loss. Electrothermal wires were linked between the outside of fireproof brick and the inside of kiln after the truck was pushed into the stove. Therefore, the heat can be conducted between upper and lower sides and the temperature distribution could be more homogenous.

2.3.2.4. *Post-treatment system*. The post-treatment system of the on-site thermal desorption process mainly consisted of condenser, condensation water tank, buffer tank and sulfur-impregnated activated carbon tank. The specifications of each treatment device are listed in Table 3.

2.4. Analytical methods

The analytical methods of the mercury in soil and water effluents were according to Standard Method 3321 [9] and Method 7471b of USEPA [10], respectively.

3. Results and discussion

3.1. The results of pilot plant test

3.1.1. Mercury vapor yield test (1a)

The experiment of mercury vapor yield test was carried out in quadruplicates. The evacuation flow rate was set at 1.35×10^{-4} m³/min and the mercury vapor yield was 5.278 mg/m³ on average. The theoretical saturation concentration of mercury vapor was 13.2 mg/m³, therefore, the saturation extent has reached about 40%. An evacuation pump was used as mercury vapor generation device in the following activated carbon breakthrough test.

3.1.2. Breakthrough test of activated carbon absorption (1b)

The activated carbon absorption experiment results showed that the sulfur-impregnated activated carbon adsorbent [11,12] achieved better adsorption efficiency than ion exchanging resin and activated carbon. As shown in Fig. 4, when 8 g activated carbons were passed through by mercury vapor for 360 min, the accumulated amount of the mercury adsorption was 0.257 mg and the emission mercury concentration 0.0037 mg/m³ was below the effluent standard.

3.1.3. Condensed water coagulation test (1c)

The condensed water coagulation experiment was carried out in two runs as shown in Table 4. The ratio of reagents in the two runs were mercury:metal scavengers:calcium hydroxide = 1:2:2 and 1:1:1, respectively. Although more sludge have been produced in run 1c-1, its treatment efficiency was better than that of run B. Therefore, the results of operation parameters in run 1c-2 were used as the full-scale tests.

3.1.4. Thermal desorption test (1d)

The thermal desorption test on soil was carried out according to four runs shown in Table 5. When the treatment temperature was higher than 650 °C, the removal efficiency reached up to 98% and the mercury concentration in the treated soil was below the cleanup criteria of 2 mg/kg.

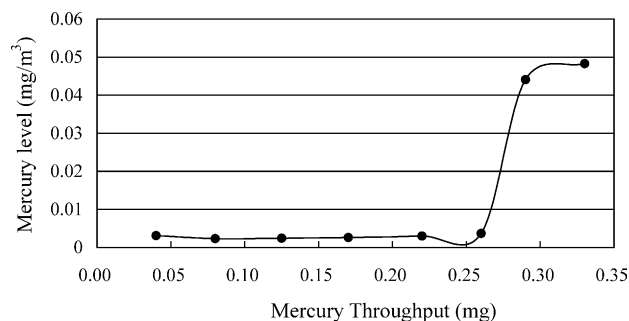


Fig. 4. Sulfur-impregnated activated carbon breakthrough curve.

Table 4
The results of condensed water coagulation

	Influent mercury concentration (mg/l)	Volume (ml)	Metal scavengers (g)	Calcium hydroxide (g)	Effluent mercury concentration (mg/l)	Removal efficiency (%)	Dry sludge (g)
Run 1c-1	1000	200	2.66	2.66	0.0054	99.9995	5.30
Run 1c-2	1000	200	1.33	1.33	145.00	85.50	2.42

Table 5
The results of thermal desorption in pilot plants

	Operation condition	Initial contaminant concentration (mg/kg)	Final contaminant concentration (mg/kg)	Contaminant removal efficiency (%)
Run 1d-1	800 °C for 1 h	140	0.53	99.62
Run 1d-2	800 °C for 1 h	78.0	0.61	99.22
Run 1d-3	250 °C for 30 min 650 °C for 1 h	74.33	0.89	98.80
Run 1d-4	300 °C for 1 h 650 °C for 1 h	41.71	0.51	98.78

3.2. The performance of on-site thermal desorption

3.2.1. Mercury concentration of the contaminated site

The survey results of mercury concentration in surface and subsurface soil of the 20 contaminated sites are showed in Table 6, which revealed that all the sites encountered different degree of mercury contamination. It was obviously observed that several sampling sites, such as L-9, L-11, L-12 and L-19 were series mercury contaminated. According to this result, the on-site full-scale thermal desorption remediation area, which was located as (A–F), were obtained by Kriging method and would be further discussed in Section 3.2.3. It was also observed that the predominant form of the mercury presented in the area was metallic mercury.

Table 6
Mercury concentration of the contaminated site

Sample number	Mercury (mgHg/kg)	
	Surface soil (0–15 cm deep)	Subsurface soil (15–30 cm deep)
L-1	2.46	1.59
L-2	4.19	1.45
L-3	1.13	0.37
L-4	7.70	19.80
L-5	2.54	2.52
L-6	0.76	1.42
L-7	2.80	27.70
L-8	3.26	20.40
L-9	94.3	73.0
L-10	8.82	3.66
L-11	124.00	74.60
L-12	42.70	27.40
L-13	6.99	2.23
L-14	16.80	7.06
L-15	0.84	1.85
L-16	23.70	0.99
L-17	65.20	34.40
L-18	1.01	0.97
L-19	0.71	0.84
L-20	1.14	0.64

3.2.2. On-site pretest experiments

The specific gravity of mercury-contaminated soil used in on-site pretest experiments was 1.7 t/m³. The soil had the appearance of brown powder similar to fine sand in wet state and mixed with brick, stone, cement block and black sludge. The cement blocks were originally from the broken pieces of the electrobath. The black sludge might be the residual mercury sludge in the original electrobath. During the excavation, it was found that the black sludge was mostly distributed within 1–1.2 m deep under the cement pavement of the original electrobath, which indicated that the bottom of the electrobath have leaked serially and the sludge that leaked out from it has contaminated the soil.

The on-site pretest results are showed in Table 7. In test 2a, the experiment was carried out with temperature of 650 °C for 3 h. The concentration of the residual mercury in soil was decreased to 5.32 mg/kg, higher than the cleanup criteria of 2 mg/kg. Therefore, the soil was treated further at a higher temperature of 700 °C for 2 h. The concentration of residual

Table 7
The pretest data of thermal desorption

Test	Feed (mg/kg)	Operation conditions	Residual mercury concentration (mg/kg)
2a	188	650 °C for 3 h	5.32
		700 °C for 2 h	1.58
2b	92.9	750 °C for 2 h	0.99
2c	135	650 °C for 2 h	5.71
		600 °C for 3 h	1.95
2d	45.5	750 °C for 2 h	0.56
		750 °C for 2 h	1.89
2e	45.5	750 °C for 3 h	0.11
		750 °C for 3 h	0.14
		750 °C for 3 h	0.05
		750 °C for 3 h	0.54
		750 °C for 3 h	0.56

mercury in the soil decreased to 1.58 mg/kg, which coincided with the regulatory criteria.

At test 2b, the original concentration of mercury in the soil was 92.9 mg/kg. After treatment at 750 °C for 2 h, the concentration of residual mercury in the soil was reduced to only 0.99 mg/kg, which indicated that a higher concentration of mercury could be decreased to below 2 mg/kg through the thermal desorption treatment at higher temperature. In addition, treatment with lower temperature and shorter time was considered. The soil was treated at 650 °C for 2 h at test 2c. The residual mercury concentration was 5.71 mg/kg, higher than the 2 mg/kg cleanup criteria, which indicated that the criteria can be achieved only with a temperature higher than 700 °C.

When the temperature was raised up to 750 °C with a retention time of 2 h at test 2d, the residual mercury concentration ranged between 0.56 and 1.89 mg/kg and all of them were below 2 mg/kg. To ensure the treatment efficiency, a series of experiments at 750 °C for 3 h were carried out. Five batches of samples were treated at this condition at test 2e and the results were quite well. The concentration of residual mercury in all the treated soil was below 1 mg/kg, even as low as 0.05 mg/kg. Table 8 showed the mass balance of test 2e, which revealed that the mass balances was about 98% and the recoveries of mercury were over 97%. This indicated that the operating performance of the thermal desorption system was quite steady.

3.2.3. Full-scale on-site remediation test

According to the soil mercury concentration survey result, the on-site full-scale thermal desorption remediation area and treated contaminated soil volume of sites (A–F), were showed in Table 2. Additionally, the optimized operation conditions of 750 °C for 3 h, which was obtained from the on-site pretest experiments, were used in the full-scale on-site remediation test. Table 9 showed the long-term overall full-scale on-site remediation of the six sites. In Table 9, it was observed that the removal efficiencies from November 2001 to January 2003

were between 96.12 and 99.84% and the mercury concentrations after remediation were all below the criteria. Table 10 was the overall mass balances of the on-site full-scale thermal desorption remediation of the six sites. It could be observed that the mass balance was about 97% and the recovery of mercury was over 96%. Fig. 5 showed the comparison of mass balance between on-site pretest and on-site full-scale thermal desorption remediation which revealed that most mercury was concentrated in the dewatering sludge in both process.

3.3. Environment management and emergency response

In order to understand whether the on-site works were in accordance with the expected goal, every procedure was monitored to prevent environmental pollution. The treated soil was covered by canvas in the site and the piling location was marked by a signboard. All the documents were computerized.

3.3.1. Industrial safety and hygiene

The on-site work has complied with workers safety and hygiene regulations. All the workers in the working site must be equipped with safety utensil to protect the head, the eyes, the breath, the hands, the feet and the body. The workshop must be airy and equipped with fire extinguishers and activated carbon adsorption devices. The dust on the ground and adsorbed on the devices must be cleaned regularly.

3.3.2. Emergency response

Sometimes, the mercury concentration after the thermal desorption ranged from 2 to 5 mg/kg, which was higher than the cleanup criteria 2 mg/kg during the remediation. Such soil was further mixed with soil in which the mercury concentration was reduced below 1 mg/kg according to the ratio 1:3 and could be returned back to the site. The soil with mercury concentration higher than 5 mg/kg must be returned to oven for further treatment.

Table 8
Mass balances and mercury recovery of pretest experiment test 2e

Items	Name	Quantity	Mercury concentration	Mercury (g/day)	Percentage (%)	Mass balance = mercury (2 + 3 + 4 + 5 + 6 + 7) / mercury(1)	Mercury recovery = mercury(3 + 5 + 6) / mercury(1)
1	Initial contaminant concentration	13.50 t/day	95.00 mg/kg	1282.50	1282.50/1282.50 = 100%	97.99%	97.07%
2	Final contaminant concentration	11.50 t/day	1.00 mg/kg	11.50	11.50/1282.50 = 0.897%		
3	Activated carbon (off gas treatment)	10.00 kg/day	1004.50 mg/kg	10.05	10.05/1282.50 = 0.784%		
4	Exhaust gas	3.20 m ³ /min	0.05 mg/m ³	0.23	0.23/1282.50 = 0.018%		
5	Dewatering sludge	5.20 kg/day	237100 mg/kg	1232.92	1232.92/1282.50 = 96.13%		
6	Activated carbon (wastewater treatment)	2.00 kg/day	1004.50 mg/l	2.01	2.01/1282.50 = 0.160%		
7	Effluent	2000 l/day	0.01 mg/l	0.02	0.02/1282.50 = 0.002%		

Table 9
The long-term performance of on-site thermal desorption

Time	Criteria (mg/kg)	Mercury concentration before remediation (mg/kg)	Mercury concentration after remediation (mg/kg)	Efficiency (%)
November/2001	2	65.1	0.37	99.43
December/2001	2	72.4	0.899	98.76
January/2002	2	211	0.359	99.83
February/2002	2	170.7	0.274	99.84
March/2002	2	21.2	0.378	98.22
April/2002	2	110.6	0.45	99.59
May/2002	2	140.9	0.575	99.59
June/2002	2	34.3	0.721	97.90
July/2002	2	29.9	0.936	96.87
August/2002	2	25.1	0.34	98.65
September/2002	2	22.6	0.493	97.82
October/2002	2	21.8	0.845	96.12
November/2002	2	19.6	0.204	98.96
February/2002	2	19.2	0.193	98.99
January/2003	2	15.3	0.203	98.67

Table 10
Mass balances and mercury recovery at an on-site full-scale thermal desorption remediation

Items	Name	Quantity	Mercury concentration	Mercury (g/day)	Percentage (%)	Mass balance = mercury (2 + 3 + 4 + 5 + 6 + 7) / mercury(1)	Mercury recovery = mercury(3 + 5 + 6) / mercury(1)
1	Initial contaminant concentration	16.00 t/day	95.00 mg/kg	1520.00	$1520.00/1520.00 = 100\%$	97.35%	96.41%
2	Final contaminant concentration	14.00 t/day	1.00 mg/kg	14.00	$14.00/1520.00 = 0.92\%$		
3	Activated carbon (off gas treatment)	10.00 kg/day	1004.50 mg/kg	10.05	$10.05/1520.00 = 0.66\%$		
4	Exhaust gas	3.20 m ³ /min	0.05 mg/m ³	0.23	$0.23/1520.00 = 0.02\%$		
5	Dewatering sludge	6.3 kg/day	230,700 mg/kg	1453.41	$1453.41/1520.00 = 95.62\%$		
6	Activated carbon (wastewater treatment)	2.00 kg/day	1004.50 mg/l	2.01	$2.01/1520.00 = 0.13\%$		
7	Effluent	2000 l/day	0.01 mg/l	0.02	$0.02/1520 = 0.001\%$		

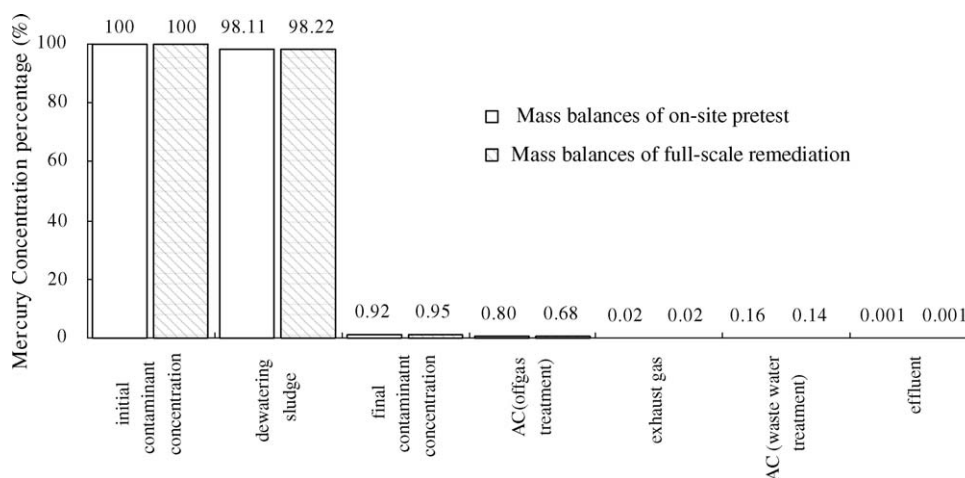


Fig. 5. Mass distribution in bass balance between on-site pretest and on-site full-scale thermal desorption remediation.

Table 11
Costs of mercury thermal desorption system (years 2002–2003)

Items	Description	Cost (US\$)	Percentage (%)
A	Construction cost	1364000	38.35
A1	Facility	137000	3.86
A2	Equipment (thermal desorption, condenser, off gas treatment)	948000	26.65
A3	Machines	57000	1.60
A4	Building worker	15000	0.42
A5	Safety and hygiene equipment	15000	0.42
A6	Electricity	20000	0.56
A7	Test run and equipment improvement	86000	2.42
A8	Management	86000	2.42
B	Operating and maintenance costs (operation worker, equipment maintenance, electricity, environmental monitoring, etc.)	1989000	55.92
C	Closing cost (environmental monitoring, waste treatment, electricity, transportation, etc.)	204000	5.73
D	Total cost	3557000	100
E	Unit cost = total cost/total treated soil = US\$ 3,557,000/4264 m ³	834	

Note: (1) mercury-contaminated soils totally treatment 4264 m³; (2) treatment cost US\$ 834/m³ of soil; (3) a soil cleanup criterion is 2.0 mg/kg for mercury.

A Typhoon landed on the site on September of 2001 during the experiment. As the typhoon alarm was announced, emergency response of standard of operating procedure was carried out and the site was not influenced by the typhoon. The stove stopped operating according to the emergency program when the earthquake occurred on March 31, 2002, which also avoided damage to the devices. During remediation, there was only once that the fuse wire was broken and thereafter was fixed. After that, the electricity supplies and power generator turned back to normal.

3.3.3. Sludge management

The mercury concentration of the concentrated sludge produced by thermal desorption was very high, ranging from 31.7×10^3 to 126.0×10^3 mg/kg. A 38 kg of sludge was produced everyday and total 2000 kg was produced during the whole remediation. The sludge was stored in sealed PE barrels for storage and the security fence was set around the area. The people or machinery passing in and out this storage area was alarmed by yellow marks indicating hazardous wastes for further disposal.

3.3.4. Activated carbon treatment

Sulfur-impregnated activated carbon (HGR) was used in the site for mercury removal. The mercury in exhaust gas and wastewater were treated by two groups of activated carbon that was comprised of six tanks with 50 kg activated carbon each. An experiment by Liu et al. [13] showed that HGR could absorb 2200 µgHg/g. According to pilot plant test, however, HGR activated carbon purchased from China Carbon Company could adsorb 2500 mgHg/kg. During the remediation, the activated carbon was changed when its absorption amount reached to 1000 mg/kg, 50% of the saturated adsorption amount, to ensure the effect of treatment. Totally, 5185 kg of activated carbon was consumed for the whole remediation. About 1.2 kg waste activated carbon, which would be put into stove for desorption, was produced for treating every cubic meter of soil.

3.3.5. Equipments and pipes disposal

When the remediation project was finished, all equipments and pipes of the thermal desorption system were dismantled and cleaned with acid solution.

3.4. Costs of the thermal desorption process

The costs of thermal desorption are highly application specific and depend on the type and scale of the system, the quantity of soil at the site, soil geotechnical properties, regulatory requirement, soil moisture content, the concentration of mercury contamination and soil cleanup criteria. The cost analysis of the full-scale thermal desorption remediation from November 2001 to January 2003 was carried out in this study, as shown in Table 11.

The cost analysis was divided into three categories: the construction cost, the operating and maintenance costs and the closing cost. The construction cost, consisting of workshop building, devices fabricating, labor for construction and electricity, was accounted for US\$ 1,364,000 (38.35%). The operating cost, consisting of labor for operation, device maintenance, electricity, devices for security, monitoring of environment, was summed up to US\$ 1,989,000 (55.92%). The factory closing cost, consisting of labor, security devices, waste treatment, transportation, environmental monitoring and electricity, etc., was added up to US\$ 204,000 (5.73%). This revealed that the total costs were US\$ 3,557,000 and the unit cost of on-site remediation work treating 4174 m³ of soil was estimated to be US\$ 834/m³ of soil. Thus, the overall remediation cost was 274 US\$/t in this study. This cost is a little higher than other remediation methods, such as the thermal enhanced soil vapor extraction method of US\$ 30–130 per cubic foot soil and the steam injection method, six-phase heating method and thermal conduction method of below US\$ 100 per cubic yard soil [14]. This might be due to the stringent cleanup criterion of 2 mg/kg was required for the contaminated mercury remediation.

4. Conclusions

This study using thermal desorption process to cleanup a mercury-polluted site in the southern part of Taipei City. The temperature and time were found to be the most important factors on the thermal desorption treatment of mercury in soil. As the temperature increases, the equilibrium concentration of mercury in the soil decreased. A temperature of higher than 700 °C and a retention time of at least 2 h were found to be effective for the thermal removal of contaminated mercury in soil. The cost analysis showed that the unit treatment price of mercury-contaminated soil was US\$ 834 slightly higher than the results from the other investigations. The main reason is that the stringent cleanup criterion of 2 mg/kg was required for the contaminated mercury remediation.

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