

REAL-TIME ELEMENTAL MERCURY VAPOR LEVELS IN AN INDOOR TEST ENVIRONMENT

Sharifah Mazrah **Sayed Mohamed Zain**^{1*}, Rafiza **Shaharudin**¹

¹*Environmental Health Research Centre, Institute for Medical Research, National Institutes of Health, Ministry of Health Malaysia, Jalan Setia Murni U13/52, Seksyen U13 Setia Alam, 40170 Shah Alam, Selangor, Malaysia*

*Corresponding author: sh.mazrah@moh.gov.my

ABSTRACT

This study measured elemental mercury (Hg^0) vapour concentrations released from a known amount of Hg^0 , simulating various thermometer and sphygmomanometer spillage scenarios in an indoor test environment. A volume of 0.15 mL and 5 mL Hg^0 spills were tested at $25\pm 1^\circ\text{C}$ and $30\pm 1^\circ\text{C}$ room temperature, measured at different heights and distances from the spills. Hg^0 vapour concentrations were measured in real-time using a Mercury Survey Meter EMP-2 with an interval of 30 min for two hours. The average concentration of Hg^0 vapour emitted from the 0.15 mL spill was between $0.1\pm 0.3 \mu\text{g m}^{-3}$ and $6.6\pm 11.0 \mu\text{g m}^{-3}$, whereas the 5 mL Hg^0 spill showed a higher range from $1.0\pm 0.3 \mu\text{g m}^{-3}$ to $24.8 \pm 8.5 \mu\text{g m}^{-3}$. The difference in Hg^0 concentration between a large spill and a small spill at 25°C and 30°C were 11.4 and 8.6 times higher, respectively. The average test room concentrations ranged from $0.4 \mu\text{g m}^{-3}$ to $16.8 \mu\text{g m}^{-3}$, exceeding the Agency for Toxic Substances and Disease Registry chronic minimal risk level of $0.3 \mu\text{g m}^{-3}$. The Mann-Whitney U test revealed a significant difference in the median Hg^0 concentration between the spill amount ($p < 0.032$) and room temperature ($p < 0.005$). This study successfully provides an estimate of mercury spill levels caused by the breakage of a thermometer or sphygmomanometer implying that a small or large spill in a warm room with low ventilation could result in significantly higher levels of Hg^0 vapour, posing a risk to human health.

KEYWORDS: Thermometer, Sphygmomanometer, Spill, Indoor Air, Tropical Climate

INTRODUCTION

Mercury is a naturally occurring chemical element found in the rock of the earth's crust. It exists in three forms: (1) elemental mercury (Hg^0), (2) inorganic mercury compounds (e.g., mercuric chloride, mercuric sulfide), and (3) organic mercury compounds (e.g., methylmercury, phenylmercury). Hg^0 is slightly volatile at room temperatures and significantly more volatile when heated (ATSDR, 1999; CDC, 2005; WHO, 2014). Both liquid and vapour forms of Hg^0 are poorly absorbed through human skin, even in high concentrations, and it is essentially nontoxic when ingested by humans as less than 0.1% is absorbed. However, inhalation has become the most significant and concerning route of human exposure towards Hg^0 , since once Hg^0 vapour is inhaled, the lungs absorb the inhaled vapour up to about 80% and carry it into the blood system (ATSDR, 1999; CDC, 2005; WHO, 2000). Higher exposure levels (e.g., 10 – 100 $\mu\text{g m}^{-3}$) over prolonged periods are associated with personality changes, memory loss, insomnia, and depression (ATSDR, 2009). At low-level exposures, nonspecific symptoms like weakness, fatigue, anorexia, and weight loss have been reported (ATSDR, 1999). The International Agency for Research on Cancer (IARC), and the Environmental Protection Agency (EPA) have not had sufficient evidence to either classify Hg^0 as a carcinogen or a noncarcinogen (ATSDR, 1999; CDC, 2005).

Despite its toxicity, the unique characteristics of Hg^0 have made it useful in many applications, such as in common medical measuring devices including thermometers and sphygmomanometers (ATSDR, 1999; CDC, 2005; UNEP, 2008). The Minamata Convention on mercury stated that by 2020 there would be no import, export, or manufacturing of medical equipment containing Hg^0 such as thermometers and sphygmomanometers (UNEP, 2019). However, the remaining Hg^0 -containing devices are still being used in many health facilities, universities and private residences. These devices would pose a significant risk to the surrounding personnel in terms of breakage and long-term disposal (UNEP, 2008; Sodeno 2023). If the Hg^0 -containing devices are mishandled, they can break and cause the liquid Hg^0 to spill, which often causes accidental exposure to Hg^0 (ATSDR, 1999; CDC, 2005; Pandey et al., 2011). Zeitz et al., (2002) stated that 96% of 413 Hg^0 spills reported occurred at fixed locations, with the most frequent sites being schools or universities (20.3%), private residences (16.7%), and healthcare facilities (16.5%).

Most Hg^0 spill cases seem to involve thermometers, which are widely used throughout the world but easily broken (Cizdziel and Jiang, 2011; UNEP, 2015). The amount of Hg^0 in each thermometer is about 0.5 – 3.0 g, and spillage of that amount is defined as a small spill (Malaysia, 2013). Spillage of anything larger than a broken thermometer is classified as a large spill (Baughman, 2006; Malaysia, 2013; UNEP, 2015). A sphygmomanometer contains 50 – 140 g of Hg^0 (NEWMOA, 2010); it is considered a large spill if it breaks. The classification of a mercury spill as either large or small is determined by a variety of factors, including the quantity of mercury released, the type of mercury (element or compound), the location of the spill (e.g., residential, industrial, or public facility), and the surrounding conditions (e.g., ventilation, temperature, and proximity to vulnerable areas such as schools or healthcare facilities). If a large spill occurs at home or a workplace and is not adequately cleaned, the hazard may persist for a long time, as Hg^0 vapour could continue to be emitted >10 years after it was spilt (Carpi and Chen, 2001). Since the Hg^0 vapour is heavier than air, after a spill the vapour may accumulate in poorly ventilated areas (Cizdziel and Jiang, 2011). Hubbard and Tranter (2011) assessment showed that historic spills were the primary Hg^0 vapor source (76.6%) in Minnesota schools. When the Hg^0 spill occurs, there is no detectable odour from either the liquid or vapour to serve as a warning sign of hazardous concentrations. Thus, it has become a matter of great concern to many regulators where several regulatory authorities have recommended limiting exposure to Hg^0 vapour to prevent occupational diseases or other adverse health effects over a specified duration of exposure as shown in Table 1 (ACGIH, 2012; ATSDR, 1999; DOSH, 1994; NIOSH, 2014; OSHA, 2005; USEPA, 1995).

While acceptable exposure limits have been developed for Hg^0 vapour in the air, information on concentrations released from an ordinary fever thermometer or Hg^0 sphygmomanometer is still scarce. There are currently many published data on indoor occupational exposures (Eustace et al., 2004; Marcotte et al., 2017; Nagpal et al., 2017; Yuyun et al., 2013), and residential exposures to airborne Hg^0 (Gyamfi et al., 2020; Morrison, 2007). However, very few investigators have measured Hg^0 vapour concentrations generated by known amounts of Hg^0 (Bigam et al., 2008; Hickson et al., 1993; Winter, 2003). None of the previous studies were conducted under tropical climate conditions, such as in Malaysia, which generally has higher indoor temperatures (28°C - 32°C) (Jamaludin et al., 2015) and relative humidity (40% – 70%) (Gonzalez and Mohd Sahabuddin, 2019). There have been multiple incidents of Hg^0 spills across Malaysia. A notable case involved a 50 mL of Hg^0 spill on the floor of a classroom 2016 (Penang), followed by another spill in a residential area (Penang) a sphygmomanometer leaked in a clinic (Kuching), and another broke in a Polytechnic (Penang) (Ibrahim and Puvanah, 2016). The most recent mercury spill resulting from a broken thermometer took place in a school in Penang in 2023 (Nusi, 2023) and at Airport Terminal in Kota Kinabalu in 2024 (Nabalunews, 2024). Although there is limited publication of precise spill data, Hg^0 exposure continues to be a concern in Malaysia due to its

toxic effects. Hence, it is imperative to provide data regarding the concentrations of Hg^0 in indoor air released from a known amount of Hg^0 in a tropical climate setting, to have a comprehensive understanding of the levels and associated risks. This experiment aims to measure the Hg^0 vapour levels in an indoor test environment, simulating a small and large spill in a low-ventilated room in tropical climate conditions. Measurements were carried out at different temperatures, various heights and distances from the source of spill and Hg^0 concentrations were compared with permissible exposure limits, and other spill cases.

Table 1. Recommended exposure limit for Hg^0 airborne concentrations set by several regulatory authorities.

Airborne concentration ($\mu\text{g m}^{-3}$)	Description	Reference
10,000	Immediately dangerous to life or health (IDLH)	NIOSH (2014)
100	Permissible exposure limit (PEL), 8-hour time-weighted average (TWA8)	OSHA (2005)
25	Permissible exposure limit (PEL), 8-hour time-weighted average (TWA8)	DOSH (1994)
25	Threshold limit value (TLV), averaged over an 8-h working shift	ACGIH (2012)
10	Recommended exposure limit (REL), averaged over a 10-h working shift	NIOSH (2014)
0.3	Reference concentration (RfC), an estimate of a continuous inhalation exposure that is likely to be without an appreciable risk of deleterious effects during a lifetime	USEPA (1995)
0.2	Minimal risk level (MRL), an estimate of daily human exposure that is likely to be without appreciable risk of adverse non-cancer health effects over a specified duration of exposure	ATSDR (1999)

NIOSH: National Institute for Occupational Safety and Health, OSHA: The United States Occupational Safety Health Administration, ACGIH: American Conference of Governmental and Industrial Hygienists, DOSH: Department of Occupational Safety and Health Malaysia, USEPA: The United States Environment Protection Agency, ATSDR: Agency for Toxic Substances and Disease Registry

MATERIALS AND METHODS

Experimental setup

This is an experimental study to measure Hg^0 vapour concentration at different spill scenarios in an indoor air environment. The Hg^0 sampling was conducted in a modified cabin with a room size of 2.9 m width x 4.0 m length x 2.2 m height. The exterior had a door in the short sidewall and a window in the long sidewall. The interior was equipped with an air conditioner, an exhaust fan, a door, and a vinyl-type floor. The schematic diagram of the experiment layout is provided in Supplementary 1 (Figure 1). Prior to the experiment, the walls and ceiling were properly sealed to prevent any openings or gaps. The door and window were closed during the sampling procedure to limit the entry of fresh air, which created a low-ventilation room environment. Reagent-grade Hg^0 >99.99% purchased from Sigma-Aldrich (USA) was used in this experiment. Room temperature ($^{\circ}\text{C}$) and relative humidity (%RH) were monitored using a Q-Trak™ Indoor Air Quality Meter Model 7565 (TSI Incorporated, Minnesota, United States). The air movement was measured using a hot wire anemometer VelociCalc® Air Velocity Meter Model 9535 (TSI Incorporated, Minnesota, United States). The range and accuracy of the devices for temperature, relative humidity and velocity were from 0 to 60 $^{\circ}\text{C}$ (± 0.6 $^{\circ}\text{C}$), 5 to 95% RH ($\pm 3\%$ RH), and 0 to 30 m s^{-1} ($\pm 3\%$), respectively, measured approximately 0.1 m and 0.75 m above the floor. The concentrations of Hg^0 vapour were measured using a portable Mercury Survey Meter Model EMP-2 (Nippon Instruments Corporation, Osaka, Japan). The EMP-2 is a real-time mercury detector with a measurement range of 0.1 – 999.9 $\mu\text{g m}^{-3}$ with 0.4 $\mu\text{g m}^{-3}$ precision. It has a response time of 1 s, which allows average concentrations to be computed internally. The EMP-2 is equipped with an internal calibration mechanism which was employed before each test condition. All of the air sampling devices used has been verified and calibrated prior to sampling and is valid during the experiment.

Measurements

All measurements were conducted between 2nd of May and 24th of May 2019. Hg⁰ vapour experiments were tested with 0.15 mL and 5 mL of liquid Hg⁰ spill. The 0.15 mL Hg⁰ corresponds to 2 g or a small spill, and the 5 mL Hg⁰ corresponds to approximately 67 g or a large spill. The small spill represents a thermometer spill, and the large spill simulates a sphygmomanometer spill. Liquid Hg⁰ was carefully placed in a Petri plate and positioned on the floor of the test room. The Petri plate kept the Hg⁰ from spreading and facilitated the cleanup process. The Malaysia Department of Standards published an MS 1525 Guideline for Malaysian climate standard indoor environment design, recommending indoor temperatures between 24°C and 26°C (Malaysia, 2014). According to a survey study, the temperature inside housing in Malaysia ranges from 28°C to 32°C (Jamaludin et al., 2015). Therefore, this study selected two temperatures within this ranges as the indoor test temperatures at approximately 25°C ± 1°C and 30°C ± 1°C. The air conditioner was switched on and adjusted to maintain the desired temperature. Measurements were taken at six points vertically and horizontally throughout the room; (i) three different height positions at 0.1 m, 0.75 m, and 1.5 m (breathing zone) above the Hg⁰ spill, and (ii) three different distances at 1 m, 2 m, and 3 m from the Hg⁰ spill at 0.75 m height. The average concentration for each test was recorded at 30 min intervals; 1 min, 30 min, 60 min, 90 min, and 120 min after the spill. The test condition parameters are summarized in Supplementary 2 (Table 1). Levels of Hg⁰ vapour was logged in µg m⁻³. The volume of the test room was 25.52 m³. Since six sampling points were set across the room, the average room concentrations were then calculated to represent the concentration of Hg⁰ for the room. The concentrations measured at 0.1 m above the Hg⁰ source (C_{0.1m}) represented the concentration from 0 to 0.2 m in height above the floor (V_{room}: 1 m long x 2.9 m wide x 0.2 m high = 0.58 m³). The concentrations measured at 0.75 m above the floor (C_{0.75m}) represented the concentration from 0.2 to 1.0 m height (V_{room}: 1 m long x 2.9 m wide x 0.8 m high = 2.32 m³). The concentrations measured at 1.5 m height above the Hg⁰ source (C_{1.5m}) represented the concentration from 1.0 to 2.2 m height (V_{room}: 1 m long x 2.9 m wide x 1.2 m high = 3.48 m³). The concentrations measured at a distance of 1.0 m (C_{1m}), 2.0 m (C_{2m}) and 3.0 m (C_{3m}) from the Hg⁰ source reflected a concentration of room volume 1 m long x 2.9 m wide x 2.2 m high = 6.38 m³ each, which covers the rest of the room. Thus, the average room concentration (C_r) was approximated by the sum of C_{0.1m}, C_{0.75m}, C_{1.5m}, C_{1m}, C_{2m}, and C_{3m} weighted by the fraction of the room volume that each of them represented, as shown in Eq. (1).

$$C_r = 0.02C_{0.1m} + 0.09C_{0.75m} + 0.14C_{1.5m} + 0.25C_{1m} + 0.25C_{2m} + 0.25C_{3m} \dots (1)$$

To minimise exposure to the highly toxic Hg⁰ and lower the risk of adverse effects, several control measures were implemented during the experimental of this study. Appropriate personal protective equipment was worn, including protective coverall with hood, nitrile gloves 0.38 mm thickness, safety goggles, covered shoes with shoe cover and half mask double respirator (3M-6200) with organic vapour/acid gas cartridges (U0301-3M-6003). After each test, the Hg⁰ spill was cleaned using a Mercury Spills Kit (Camlab, Cambridge, United Kingdom) and afterwards disposed of in accordance with local regulations. Before conducting the following test, the levels of Hg⁰ vapour in the test room were verified to be completely absent.

Statistical Analysis

Statistical analysis for the Hg⁰ spill results was performed using IBM SPSS Statistics 25. The normality was tested and observed from the frequency distribution (histogram) and the Shapiro-Wilk test. The data were not normally distributed (p<0.05); therefore, the non-parametric tests were used. A Kruskal-Wallis test was used to determine differences between the concentrations of Hg⁰ according to distance, height, and sampling time. The Mann-Whitney U test was used to compare differences between Hg⁰ amounts at different room temperatures. All statistical analysis was carried out at a 95% confidence interval. A p-value of <0.05 was considered significant.

RESULTS

A dataset of N = 120 different test conditions was obtained, with each condition having an average of at least 290 Hg⁰ concentration readings (n ≥ 290). Supplementary 3 (Table 2) provides the mean, range, and standard deviation for each test condition measured at 25°C and 30°C at different heights (C_{0.1m}, C_{0.75m}, C_{1.5m}) and distances (C_{1m}, C_{2m}, C_{3m}), at intervals of 1 min, 30 min, 60 min, 90 min, and 120 min after the small and large spills. The frequency distribution of all the Hg⁰ concentrations dataset is shown in histogram plot with an average of 7.48 ± 7.46 µg m⁻³ (Supplementary 4, Figure 2). During the sampling, the room's relative humidity varied from 40% to 63% with an air velocity of 0.11 m s⁻¹ to 0.12 m s⁻¹. The outside ambient temperature ranged from 29°C to 33°C.

Table 2: Studies on Hg⁰ vapour concentration measured in an indoor air environment using real-time mercury analyser

Source	Study site	Hg ⁰ amount and condition	Air temperature (sampling time)	Levels (µg m ⁻³)
This study	Indoor test experiment, low ventilated room, 26 m ³	• 0.15 mL, stationary	25°C, 30°C (2 h)	0.1 – 83.0
		• 5 mL, stationary	25°C, 30°C (2 h)	1.01 – 32.0
Bigham et al. (2008)	Indoor test experiment, well-ventilated room, 20 m ³ , 2.2 h ⁻¹ air change	• 0.034 mL, stationary	17°C (0.5 h)	0.26 – 0.56
		• 5 mL, stationary	19°C (0.5 h)	1.8 – 26
		• ~0.1 mm, thousand beads	22°C (2 h)	100 – 902
		• ~0.1 mm, thousand beads	10°C (140 h)	9 – 49
Winter (2003)	Indoor test experiment, well-ventilated room, 107 m ³ , 0.3 h ⁻¹ air change	• 0.015 mL, stationary	22°C	0.046
		• 0.15 mL, stationary	21.8°C – 24.2°C	4.6 – 10
Santoro (2006)	Spill case, university building	• 0.15 mL, one thermometer spill in a hot water bath, evaporated	1°C (6 h)	28 – 80
			1°C (3 days)	7 – 80
Scheepers et al. (2014)	Spill case, private residence	• 3mL, one barometer spill on the hardwood floor, cleaned using a vacuum cleaner, measured four days after the spill	19°C – 22°C	0.5 – 28.0
Morrison (2007)	Spill case, private residence	• 0.04 mL, one thermometer spill on the bedroom floor, cleaned using a vacuum cleaner, measured four days after the spill	No information	10 – 12
		• 0.22 mL, one thermostat spill on hallway wood strip floor, cleaned using wet/dry vacuum cleaner	No information	0.4 – 1.6
Carpi and Chen (2001)	Spill case, private residence	• One thermometer spill, measured 16 y after the spill	25°C (3 – 5 h)	0.045 ± 0.0007
		• One thermometer spill, measured six months after the spill	22°C (3 – 5 h)	0.52 ± 0.006

Small vs large spill at different temperatures

The average concentration of Hg⁰ vapour emitted from the small spill ranged from 0.1 ± 0.3 µg m⁻³ to 6.6 ± 11.0 µg m⁻³, while the average amount released from the large spill showed higher levels, from 1.0 ± 0.3 µg m⁻³ to 24.8 ± 8.5 µg m⁻³. The highest concentration from the small spill was 83.0 µg m⁻³, while the large spill had the highest concentration of 132.0 µg m⁻³. The Cr levels generated from the small spill were between 0.4 µg m⁻³ and 2.1 µg m⁻³, while the large spill resulted in higher Cr from 1.5 µg m⁻³ to 17.8 µg m⁻³. At 25°C and 30°C, the large spill released 11.4 times and 8.6 times higher C_r in the room, respectively, than the small spill at the same temperature (Supplementary 5, Table 3). Figure 1 showed a significant difference in C_r concentration, measured at 25°C and 30°C. The small spill and the large spill showed an increase of 1.6 times (1.0 µg m⁻³ to 1.6 µg m⁻³) and 1.2 times (11.4 µg m⁻³ to 13.8 µg m⁻³), respectively, when the temperature rose from 25°C to 30°C. The Mann-Whitney U test showed a statistical difference in the median of Hg⁰ concentration between the Hg⁰ amount and room temperature. The concentrations of Hg⁰ vapour at 30°C were significantly higher than at 25°C (Mann-Whitney U = 1.392E3, n¹ = n² = 60, Z = -2.140, p < 0.032 two-tailed) with mean ranks of 67.29 for 30°C and 53.71 for 25°C. Comparing the amount of Hg⁰, the concentrations were significantly higher for the large Hg⁰ spill than for the small spill (Mann-Whitney U = 167, n¹ = n² = 40, Z = -8.577, p < 0.005 two-tailed) with the mean ranks at 87.72 for the large Hg⁰ spill and 33.28 for the small one. Pearson correlation test revealed a

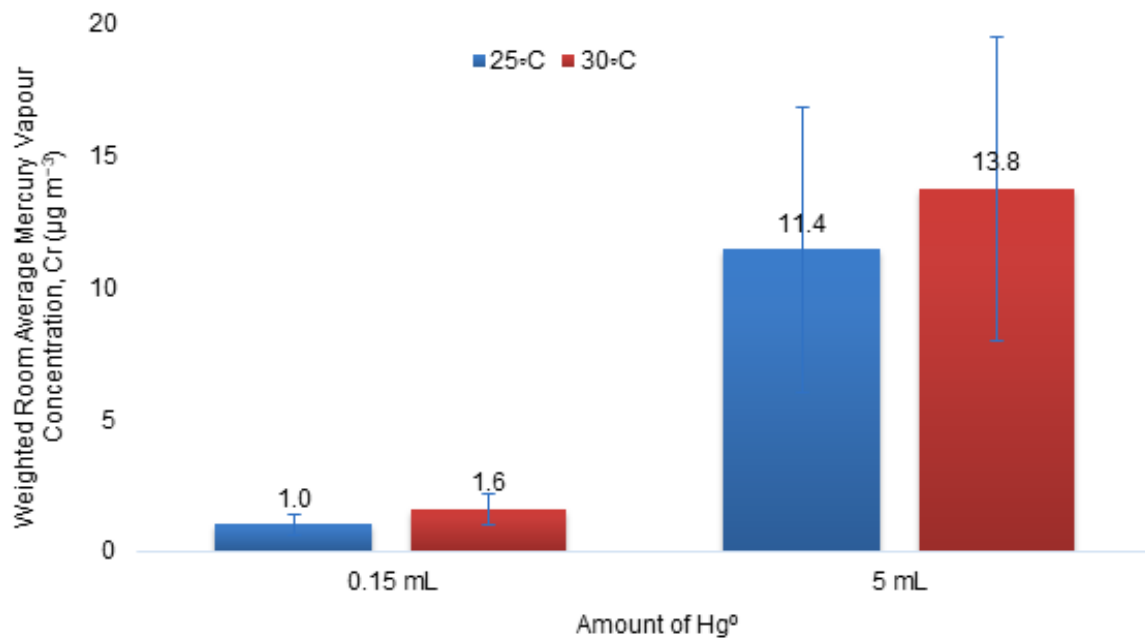


Figure 1. The weighted room average Hg⁰ vapour concentration, Cr (µg m⁻³) measured for 2-h using 0.15 mL and 5 mL liquid Hg⁰ at 25°C and 30°C with standard deviation error bars

Small vs large spill at different sampling times

The Cr concentration measured at different times (1 min, 30 min, 60 min, 90 min and 120 min) is shown in Figure 2. The pattern shows a significant rise at 30 min and reaches a peak value between 30 min and 90 min. All test samples showed a decrease at 120 minutes. At 25°C, the C_r values emitted from the large spill increased the Hg⁰ levels by 3.8 times at 1 min and up to 18.8 times at 120 min compared to the small spill. At 30°C, the large spill increased C_r concentrations by 5.4 times at 1 min to 9.2 times at 60 min as opposed to the small spill. The small spill emits a barely noticeable pattern at both temperatures, ranging from 0.4 µg m⁻³ to 1.7 µg m⁻³ in contrast, higher C_r was reported from large Hg⁰ spill, varying from 1.5 µg m⁻³ to 17.8 µg m⁻³. The Kruskal Wallis test was performed to determine the association between Hg⁰ concentrations at different sampling times (1 min, 30 min, 60 min, 90 min and 120 min). This study showed that there was a statistically significant difference in Hg⁰ concentrations between the different sampling times (X² (4) = 17.363, p = 0.02), with mean rank concentrations of 72.29 for 90 min, 68.79 for 60 min, 64.06 for 30 min, 62.35 for 120 min and 35.00 for 1 min.

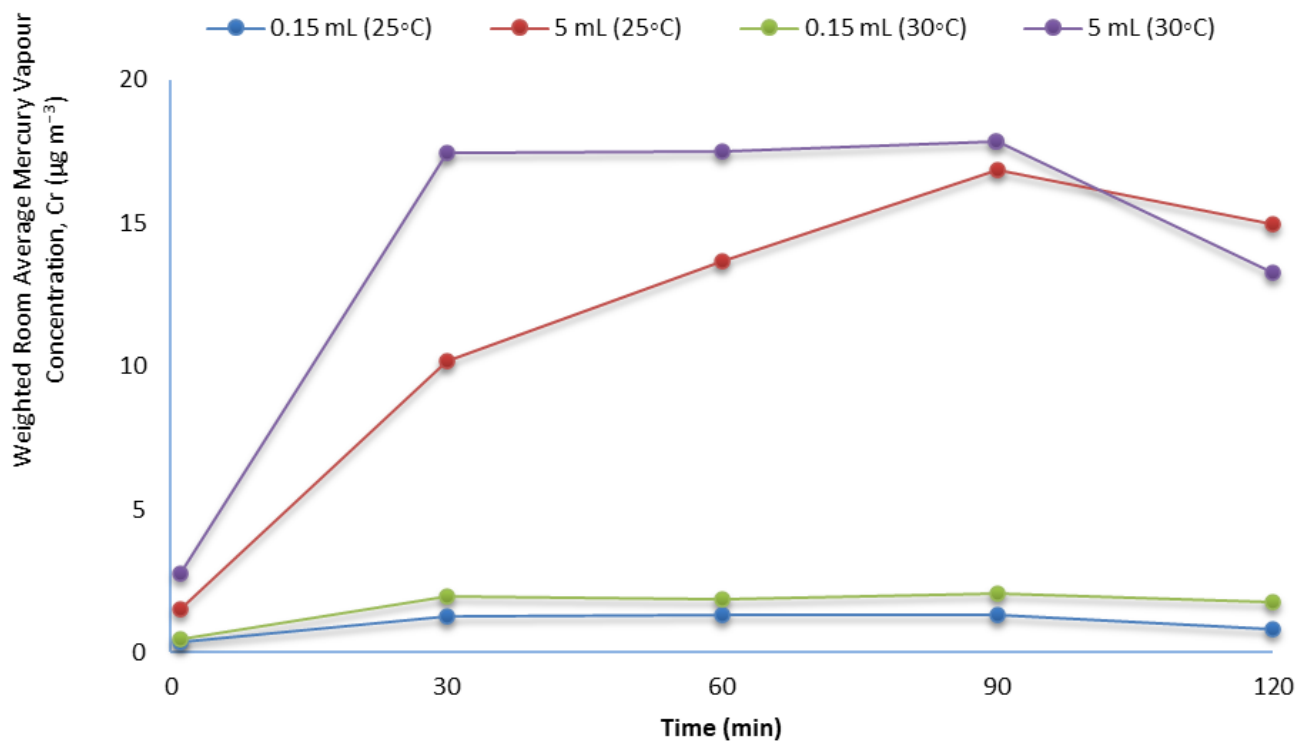


Figure 2. Graph of the weighted room average Hg^0 concentrations ($\mu\text{g m}^{-3}$) at 1 min, 30 min, 60 min, 90 min and 120 min after the spill

Hg^0 concentration at different heights and distances

The average Hg^0 levels were highest at 0.1 m above the point of the liquid Hg^0 , which ranged from $1.6 \mu\text{g m}^{-3}$ to $17.5 \mu\text{g m}^{-3}$. The levels gradually reduced at 0.75 m and were lowest at 1.5 m height above the source, between $0.5 \mu\text{g m}^{-3}$ and $14.8 \mu\text{g m}^{-3}$ (Figure 3a). At 25°C , the large spill shows an increase from 9.4 times (at 0.1 m height) to 24.6 times (at 1.5 m height) higher than the small spill. In contrast, at 30°C , the increasing Hg^0 levels released from the large spill was not apparent compared to the small spill; between 5.5 times (at 0.1 m) and 8.7 times (at 1.5 m) higher. The average Hg^0 concentrations measured at different distances (0 m, 1 m, 2 m, and 3 m), at 0.75 m height from the Hg^0 source are shown in Figure 3b. The trend shows a slight decrease of Hg^0 levels with an increase of distance. At 25°C , the large spill shows an increase from 6.3 times (at 1 m distance) to 21.2 times (at 3 m distance) higher vapour concentration than the small spill. However, at 30°C , Hg^0 levels released from the large spill were between 7.2 times (at 3 m distance) and 13 times (at 1.5 m) higher than the vapour released from the small spill.

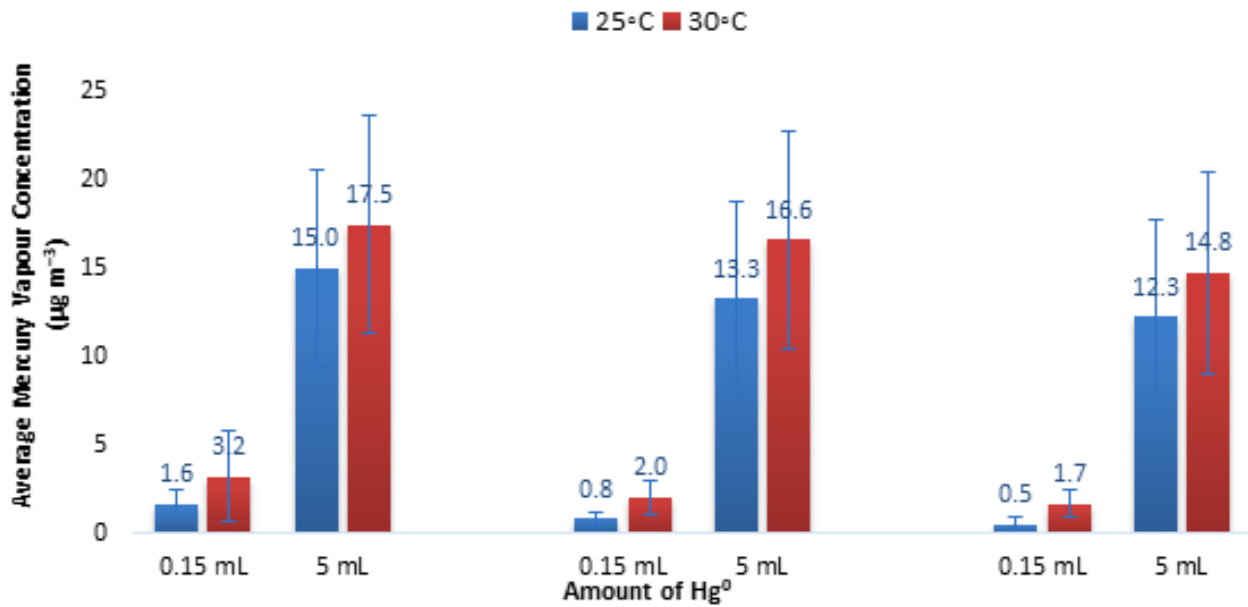


Figure 3a. Average Hg⁰ vapour concentration (µg m⁻³) emitted from 0.15 mL and 5 mL Hg⁰ measured at 0.1 m, 0.75 m and 1.5 m height above the source with standard deviation error bars

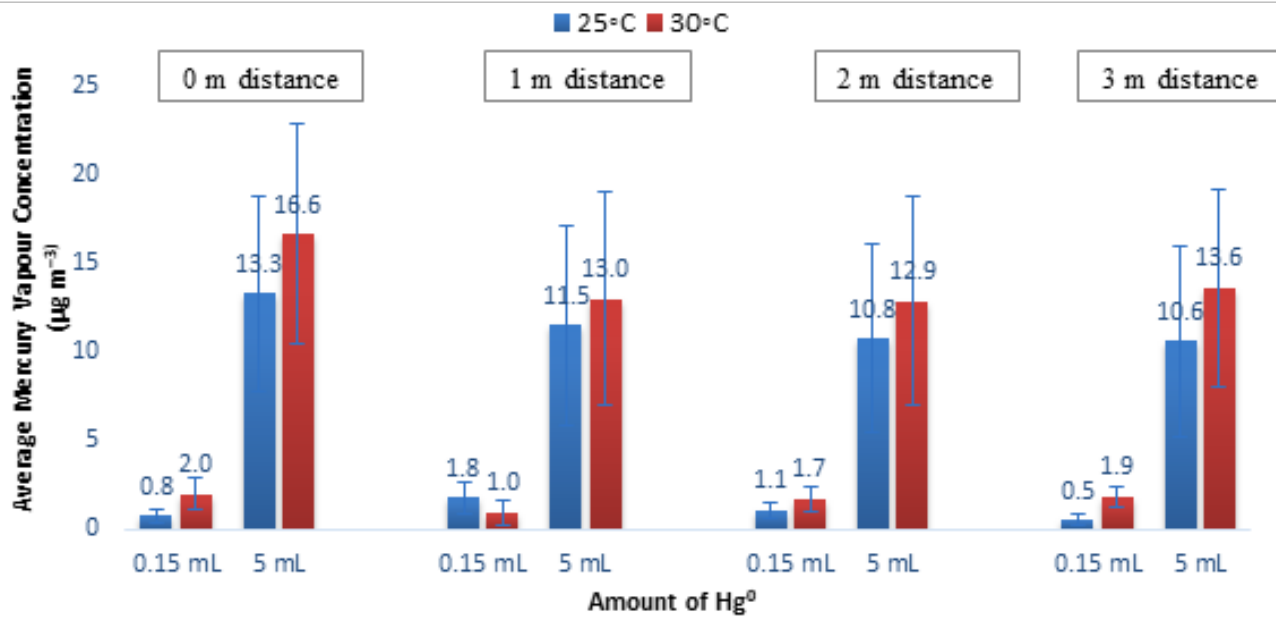


Figure 3b. Average Hg⁰ vapour concentration (µg m⁻³) emitted from 0.15 mL and 5 mL Hg⁰ measured at 0.75 m height at the point of source, 1 m, 2 m, and 3 m distance from the source with standard deviation error bars

DISCUSSION

Generally, the Hg⁰ concentrations varies at different heights and distances over time. The findings demonstrated that the room temperature and the volume of Hg⁰ have a substantial impact on the levels of Hg⁰ vapour released into indoor air. Higher temperature and a greater amount of Hg⁰ were the significant factors in increasing the levels of Hg⁰ in a low-ventilated room. The greater the Hg⁰ amount, the larger the surface area, thus increasing the Hg⁰ evaporation into the air (Bigham et al. 2008). Winter (2003) and Bigham et al. (2008) reported the same trend where higher temperatures and larger Hg⁰ amounts lead to greater levels of Hg⁰ vapour released into the atmosphere.

The small difference emitted from the small spill at both temperatures was explained by Reinke and Brosseau (1996)

where changes in room temperature during evaporation of a substance are assumed to be negligible for the low generation rate of a small spill. The downward trend with time might have been due to the oxidation of Hg^0 , as stated by several investigators (Hickson et al. 1993; Winter 2003; Bigham et al. 2008). Bigham et al. (2008) suggested that the oxidation of liquid Hg^0 in air follows a similar mechanism of water vapour. The author also found that the downward trend corresponds to the time constant of days. The effect of oxidation is less visible in hourly readings, but more noticeable on a daily rather than hourly basis. This explains a slight reduction found at 120 min in this paper, which is a measurement of 2 hours rather than an observation of days. Nonetheless, the decreasing trend is statistically significant, indicating that high temperatures and little ventilation in the test room may accelerate the oxidative process of liquid Hg^0 ; hence, the decreasing trend is visible at 120 min.

This study shows that the Hg^0 levels were highest at 0.1 m above the Hg^0 source and 0 m distance (at the point of source). The same findings were reported by other investigators, namely that Hg^0 vapour levels were highest at the point above the Hg^0 spill source (Winter 2003; Bigham et al. 2008). A Kruskal Wallis test was performed to determine the association between Hg^0 concentrations at different heights (0.1 m, 0.75 m and 1.5 m), and distances (0 m, 1 m, 2 m, and 3 m). The test revealed no statistical difference between the distances and heights in the median Hg^0 concentration. This indicates that if a Hg^0 spill occurs in a corner of a warm and poorly ventilated room, the readily vapourising nature of Hg^0 may allow the vapour to accumulate in the air, occupying the entire space and give significant human exposure to a person in the room, even if they are not near to the source of the spill.

The measurements obtained from both small and large Hg^0 spills were significantly below than the immediately dangerous to life or health (IDLH) limit of $10,000 \mu\text{g m}^{-3}$ set by the National Institute for Occupational Safety and Health (NIOSH 2014). Considering residential exposure scenarios, this study discovered that the Cr concentrations exceeded both the reference concentration (RfC) limit of $0.3 \mu\text{g m}^{-3}$ stipulated by the United States Occupational Safety Health Administration (USEPA, 1995), and the minimal risk level (MRL) limit of $0.2 \mu\text{g m}^{-3}$ set by the Agency for Toxic Substances and Disease Registry (ATSDR, 1999), a level that protects public health in residential exposure situations. In terms of occupational exposure scenarios, the Cr concentrations emitted from the large Hg^0 spill at both temperatures exceeded the recommended exposure limit (REL) of $10 \mu\text{g m}^{-3}$ determined by the National Institute for Occupational Safety and Health (NIOSH 2014). At a temperature of 30°C , the large Hg^0 spill released concentration of $24.8 \mu\text{g m}^{-3}$, which almost exceeding the 8-hour time-weighted average (TWA8) exposure limit of $25 \mu\text{g m}^{-3}$ established by both the Department of Occupational Safety and Health Malaysia (DOSH, 1994) and the American Conference of Governmental and Industrial Hygienists (ACGIH, 2012). Nevertheless, the concentrations measured were lower than the TWA8 permissible exposure limit of $100 \mu\text{g m}^{-3}$ set by the United States Occupational Safety Health Administration (OSHA, 2005). These regulatory limits were established based on the average duration of 8-hour and 10-hour work shifts. Therefore, this finding indicates that if mitigation action is delayed after a large spill in a warm and poorly ventilated room, it poses a significant risk of Hg^0 exposure to surrounding personnel in the area.

Table 2 shows the Hg^0 air concentrations reported by several researchers measured in an indoor air environment using a real-time mercury analyser. This study is similar to the indoor test experiment conducted by Winter (2003) and Bigham et al. (2008) using 0.15 mL and 5 mL liquid Hg^0 , respectively. This study showed higher levels of Hg^0 vapour emitted from 5 mL Hg^0 ($1.0 - 132.0 \mu\text{g m}^{-3}$) compared to the same amount reported by Bigham et al. (2008) ($1.8 - 26 \mu\text{g m}^{-3}$). Similarly, this study also showed higher concentrations ($0.1 - 83.0 \mu\text{g m}^{-3}$) released from 0.15 mL Hg^0 , compared to the same amount published by Winter (2003) ($4.6 - 10 \mu\text{g m}^{-3}$). The reason might be due to the higher test room temperatures in this study (25°C and 30°C) and low air-exchange resulting in high Hg^0 levels compared to the other two similar studies using lower room temperatures ($19^\circ\text{C} - 24.2^\circ\text{C}$) and a well-ventilated room. Bigham et al. (2008) reported high levels of Hg^0 vapour when the 5 mL liquid Hg^0 was swept with a broom, causing the liquid Hg^0 to disperse and form thousands of small beads, accelerating the vaporisation (Reinke and Brosseau 1996), thus increasing the levels to above $100 \mu\text{g m}^{-3}$, which was within the range of this study.

This study was compared with actual spill cases, as described in Table 2. Hg^0 levels emitted from the small spill ($0.1 - 83.0 \mu\text{g m}^{-3}$) showed a similar range with a thermometer spill case reported by Santoro (2006) ($28 - 80 \mu\text{g m}^{-3}$). Several studies reported low Hg^0 levels in residential buildings after six months and a trace level 16 years after a thermometer spill event occurred (Carpi and Chen 2001; Morrison 2007). Although the Hg^0 spill was removed, it still exists in the air. The persistence of Hg^0 vapour in indoor air is caused by a few factors: (1) Hg^0 droplets have a tendency to create little beads that spread out and can potentially into cracks, resulting in a challenging cleaning process and (2) over time, Hg^0 has a tendency to permeate building materials and is typically unable to be extracted from porous substances such as carpets, textiles, fibreboard, untreated wood, and upholstered furniture (Baughman 2006). This suggests that even a small Hg^0 spill at home might pose a long-term risk to the residents, especially if the clean-up is not carried out intensively and the Hg^0 vapour continually persists in the air. Similarly, the Cr concentrations from the large spill were

comparable to those reported in hospital buildings in Indonesia where broken sphygmomanometers were fixed (Yuyun et al. 2013). The study comparison suggested that the small and large Hg⁰ spill test presented in this study, which simulate a thermometer and sphygmomanometer spill, are comparable to actual spill incidences for a fever thermometer and sphygmomanometer. It is noted that the published data on mercury-related issues has significantly decreased in recent years due to stricter regulations and the substitution of mercury-containing devices with safer alternatives. Hence, the need for further research has lessened, resulting in a scarcity of published data on this topic in the past few years.

CONCLUSION

The results indicated that both large or small Hg⁰ spills in warm room temperatures with poor ventilation could result in substantially higher amounts of Hg⁰ vapour, which can potentially risk human health. Although the use of thermometers and sphygmomanometer has declined since the enactment of the Minamata Convention on Mercury in 2017, homeowners and facility managers should identify devices containing Hg⁰ and, where possible, replace them with Hg⁰-free substitute products. It takes very little Hg⁰ to create unsafe vapour levels in the surrounding air. Nevertheless, it must be noted that Hg⁰ levels in our experiments are representative of the conditions for spill described in this article. It is important to consider both the effects of environmental parameters and the characteristics of spilled Hg⁰ when evaluating the Hg⁰ vapour under other conditions.

ACKNOWLEDGEMENT

The author would like to acknowledge for the financial support by a grant from the Institute for Medical Research, National Institutes of Health, funded by the Ministry of Health Malaysia, Malaysia (NMRR-17-1164-36197). The authors would like to express our gratitude to the Director General of Health Malaysia and the Director Institute for Medical Research for their permission to publish this paper. This research is supported Thanks to the Occupational Safety and Health Unit, Ministry of Health Malaysia for initiating this project. Deepest appreciation to the Environmental Health Research Centre, Institute for Medical Research, Malaysia and Industrial Hygiene and Ergonomics Division, Department of Occupational Safety and Health, Ministry of Human Resources Malaysia for their cooperation, support, and permission to use the required equipment to complete the task.

REFERENCES

- ACGIH. 2012 Threshold Limit Values (TLVs) for Chemical Substances and Physical Agents and Biological exposure Indices (BEIs). American Conference of Governmental Industrial Hygienists. Cincinnati, Ohio, 2012
- ATSDR. Toxicological Profile for Mercury. Agency for Toxic Substances and Disease Registry. Atlanta, Georgia United States: Department of Health and Human Services, 1999. <https://www.atsdr.cdc.gov/toxprofiles/tp46.pdf>
- ATSDR. Children's Exposure to Elemental Mercury. A National Review of Exposure Events. Agency for Toxic Substances and Disease Registry. United States Department of Health and Human Services, 2009. https://stacks.cdc.gov/view/cdc/5462/cdc_5462_DS1.pdf
- Baughman, TA. 2006. "Elemental Mercury Spills." *Environmental Health Perspectives* 114(2): 147-152. <https://doi.org/10.1289/ehp.7048>
- Bigham GN, Chan WR, Dekermenjian M, and Reza A. 2008. "Indoor Concentrations of Hg Vapor Following Various Spill Scenarios." *Environmental Forensic* 9(2-3): 187-196. <https://doi.org/10.1080/15275920802121975>.
- Carpi A, and Chen YF. 2001. "Gaseous Elemental Mercury as an Indoor Air Pollutant." *Environmental Science & Technology* 35: 4170-4173. <https://doi.org/10.1021/es010749p>
- CDC. Spotlight on Mercury CDC's Third National Report on Human Exposure to Environmental Chemicals. The Centers for Disease Control and Prevention, United States, 2005.
- Choudhary R, Arnold FC, and Nguyen NT. 2012. "The Evaporation of Mercury Droplets in Indoor Spaces." *Journal of Occupational and Environmental Hygiene* 9(12): 712-719. <https://doi.org/10.1080/15459624.2012.728925>
- Cizdziel JV, and Jiang Y. 2011. "Concentrations of Gaseous Elemental Mercury in Ambient Air Within an Academic Chemistry Building." *Bulletin of Environmental Contamination and Toxicology* 86(4): 419-422. <https://doi.org/10.1007/>

s00128-011-0206-2.

DOSH. Occupational Safety and Health (Use and Standards of Exposure of Chemicals Hazardous to Health) Regulations 2000, Act 514 C.F.R. Department of Occupational Safety and Health Malaysia, 1994.

Eustace DJ, Walters M, Riley S, and Anderson M. 2004. "Practical Assessment of Mercury Exposure, Contamination and Clean-Up." *Chemical Health and Safety* 11(3): 16-23. <https://doi.org/10.1016/j.chs.2004.02.005>

Gonzalez L, and Mohd Sahabuddin MF. 2019. "High-Rise Social Housing in Hot-Humid Climates: Towards an 'Airhouse' Standard for Comfort." *Applied Sciences* 9(23): 4985. <https://doi.org/10.3390/app9234985>

Gyamfi O, Sorenson PB, Darko G, Ansah E, and Bak JL. 2020. "Human Health Risk Assessment of Exposure to Indoor Mercury Vapour in a Ghanaian Artisanal Small-Scale Gold Mining Community." *Chemosphere* 241: 125014. <https://doi.org/10.1016/j.chemosphere.2019.125014>

Hickson P, Cabanac R, and Watson SEM. "A study of mercury vapour concentrations at UBC/Laval 2.7-metre liquid-mirror observatory." Vancouver, Canada, 1993.

Hubbard C, and Tranter DC. 2011. Mercury air concentrations and sources in Minnesota (U.S.A.) schools. Paper presented at the 12th International Conference on Indoor Air Quality and Climate 2011.

Ibrahim, Izyan Diyana. and P, Puvanah. 2016. "Mercury Poisoning Cases in Malaysia". *Pharmacy Buletin* 16(10). <https://hctm.ukm.my/farmasi/wp-content/uploads/2020/09/10.2016.-pharmacy-counselling-week-2016-and-mercury-poisoning.pdf>.

Jamaludin N, Mohammed NI, Khamidi MF, and Wahab SNA. 2015. "Thermal Comfort of Residential Building in Malaysia at Different Micro-climates." *Procedia - Social and Behavioral Science* 170: 613-623. <https://doi.org/10.1016/j.sbspro.2015.01.063>.

Malaysia. Guidelines on disposing mercury containing sphygmomanometers and thermometers in Ministry of Health hospitals. Ministry of Health Malaysia, 2013.

Malaysia. Malaysian Standard MS 1525:2014 Energy efficiency and use of renewable energy for non-residential buildings - Code of practice (Second revision). Department of Standards Malaysia, 2014.

Marcotte S, Estel L, Minchin S, Leboucher S, and Le Meur S. 2017. "Monitoring of Lead, Arsenic and Mercury in The Indoor Air and Settled Dust in The Natural History Museum Of Rouen (France)." *Atmospheric Pollution Research* 8(3): 483-489. <https://doi.org/10.1016/j.apr.2016.12.002>

Morrison J. 2007. "Exposure assessment of household mercury spills." *Journal of Chemical Health and Safety* 14(1): 17-21. <https://doi.org/10.1016/j.jchas.2006.08.004>.

Nabalunews. "Tumpahan merkuri di Terminal Penerbangan Minyak Petronas". 21 August 2024. Nabalu News. <https://www.nabalunews.com/post/tumpahan-merkuri-di-terminal-penerbangan-minyak-petronas>

Nagpal N, Bettiol SS, Isham A, Hoang H, and Crocombe LA. 2017. "A Review of Mercury Exposure and Health of Dental Personnel." *Safety and Health at Work* 8(1): 1-10. <https://doi.org/10.1016/j.shaw.2016.05.007>.

NEWMOA. IMERC Fact Sheet Mercury Use in Measuring Devices, 2010. http://www.newmoa.org/prevention/mercury/imerc/factsheets/measuring_devices.cfm [Assessed 2 August 2020].

NIOSH. NIOSH Pocket Guide to Chemical Hazards, 2014 <https://www.cdc.gov/niosh/idlh/merc-hg.html> [Assessed 2 August 2020].

Nusi, Noor Hasliza. "Pelajar tingkatan 5 terkena tumpahan merkuri". 20 November 2023. Kosmo. <https://www.kosmo.com.my/2023/11/20/pelajar-tingkatan-5-terkena-tumpahan-merkuri/>

OSHA. Mercury, Occupational Safety and Health Administration (OSHA) Standards, 2005 <https://www.osha.gov/SLTC/>

mercury/standards.html [Assessed 10 August 2020].

Pandey SK, Kim KH, and Brown RJC. 2011. "Measurement Techniques for Mercury Species in Ambient Air." *TrAC Trends in Analytical Chemistry* 30(6): 899-917. <https://doi.org/10.1016/j.trac.2011.01.017>.

Reinke PH, and Brosseau LM. 1996. "Development of a Model to Predict Air Contaminant Concentrations Following Indoor Spills Of Volatile Liquids." *British Occupations Hygiene Society* 41: 415-435. [https://doi.org/10.1016/S0003-4878\(96\)00048-8](https://doi.org/10.1016/S0003-4878(96)00048-8)

Santoro A. 2006. "Mercury Spill Decontamination Incident at the Rockefeller University." *Journal of Chemical Health and Safety* 13(1): 30-37. <https://doi.org/10.1016/j.chs.2005.01.014>.

Sodeno R. 2023. "Projected global Mercury Supply, Demand, And Excess To 2050 Based on Impacts of the Minamata Convention." *Journal of Material Cycles and Waste Management* 25(6): 3608-3624. <https://doi.org/10.1007/s10163-023-01780-y>

UNEP. *Mercury Use in Healthcare Settings and Dentistry (Module 4)*. United Nations Environment Programme. Geneva Switzerland, 2008.

UNEP. *Technical guidelines on the environmentally sound management of wastes consisting of, containing or contaminated with mercury or mercury compounds UNEP/CHW.12/5/Add.8/Rev.1*. United Nations Environment Programme. Geneva Switzerland, 2015.

UNEP. *Minamata Convention on Mercury*. United Nations Environment Programme. Nairobi, Kenya, 2019.

USEPA. *Integrated Risk Information System (IRIS), Mercury, elemental; CASRN 7439-97-6 Chemical Assessment Summary*. United States Environment Protection Agency, 1995.

WHO. *Mercury Air Quality Guidelines*. World Health Organisation. Copanhamen, Denmark, 2000.

WHO. *Safe management of wastes from health-care activities*. Yves Chartier J E., Ute Pieper, Annette Prüss, Philip Rushbrook, Ruth Stringer, William Townend, Susan Wilburn & Raki Zghondi Ed. 2nd ed. World Health Organization, Geneva, Switzerland, 2014.

Winter TG. 2003. "The Evaporation of a Drop of Mercury." *American Journal of Physics* 71(8): 783-786. <https://doi.org/10.1119/1.1568971>.

Yuyun I, Krishna Z, Gita A, and Tri Wahyudi ST. 2013. "Indoor air mercury monitoring report in ten hospitals in Denpasar, Bali, Indonesia." 18 September 2013. <https://www.nexus3foundation.org/2013/09/18/indoor-air-mercury-monitoring-report-in-10-hospitals-in-denpasar-bali-indonesia/>

Zeitz P, Orr MF, and Kaye WE. 2002. "Public Health Consequences of Mercury Spills: Hazardous Substances Emergency Events Surveillance System, 1993–1998." *Environmental Health Perspectives* 110: 129-132. <https://doi.org/10.1289/ehp.02110129>