

Mercury Emissions from Polyurethane Flooring in Gymnasiums

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(ABSTRACT)

From the 1960s to the 1980s, many schools throughout the country installed synthetic flooring in indoor gymnasiums that contained mercury which was used as a catalyst in the polyurethane formulation. Many of these floors now have been found to be releasing mercury vapors into the school gymnasiums, leading to a concern that these mercury concentrations might be elevated enough to cause harmful effects. This paper examines data that have been collected from 57 different school gymnasiums using portable devices, such as the Lumex RA-915+ Portable Mercury Vapor Analyzer, and aggregated for analyses, then compares this data to that obtained in chamber tests performed on samples obtained directly from a gymnasium with mercury-containing floors.

The overall objective of this paper is to determine if the chamber tests can adequately emulate mercury emissions in school gymnasiums, and using the results of the laboratory experiments, successfully analyze the emissions curve to determine what factors drive the profile. The laboratory testing was successful in emulating the condition of a school gymnasium, as data collected from the laboratory setting was comparable to the measured field data. The average mercury concentration in the gymnasium yielded an emission rate $3.1E-05$ ug/m²s, while the calculated laboratory emission rate was $3.2E-05$ ug/m²s, a negligible difference. The overall objective was met, as it was determined that floor samples taken from a gymnasium could be measured in the laboratory with similar results to those screened in the actual gym with handheld devices. Additionally, using the data collected in the chamber experiments, the emissions profile was characterized.

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1. Background

Beginning in the 1960s, continuing throughout the 1970s, 1980s, and even into the early 1990s, many schools throughout the United States installed synthetic polyurethane flooring in indoor gymnasiums. Some of these floors contained a mercury compound which was utilized as a catalyst in the polyurethane formulation process. Many of these floors now have been found to be releasing elemental mercury vapor into the school gymnasiums. There is concern that these mercury concentrations might be high enough to cause harmful effects. The mercury concentrations are therefore being measured and evaluated to determine if they pose a health risk. This paper examines data that has been collected from a number of these school gymnasiums, and compares the aggregated data to tests performed on samples of the flooring placed in small chambers. These chamber tests will be used to address several additional objectives.

These synthetic floors were made by a variety of manufacturers, with similar but different formulations. According to one prominent manufacturer, mercury was used as a catalyst when mixing the polymer to form the floor covering, resulting in a finished product containing mercury. One such formulation resulted in a concentration of 0.1% to 0.2% by weight phenyl mercuric acetate, PMA (Reiner 2005). A sample of flooring obtained in 2006 had a density of 2.68 g/cm³ and a mercury content of 170 µg/g (ATSDR 2008). The flooring releases elemental mercury vapor; in some cases this volatilization can be particularly concentrated in ‘hot spots’ such as holes placed in the floors for equipment, or in areas of the floors that have become damaged. In fact, air testing results in gymnasium settings have varied greatly in concentrations of mercury vapor. As an example, two floors screened in 2006 at the same school complex in Michigan showed a difference by a factor of four in vapor readings though they were installed only four years apart.

Although industry-wide data have not been collected, estimates from just one manufacturer indicate that they have installed over 25 million pounds of polyurethane flooring product over the past 40 years. By this estimate, a 10,000 pound floor would mean 2500 different installations by just one of at least ten manufacturers. The United States Department of Health and Human Service’s Agency for Toxic Substances and Disease Registry (ATSDR) has been working to determine how widespread the problem is – how many schools in how many states? They are working collaboratively with their state health department partners, including Michigan, Minnesota, Ohio and Oregon, by performing public health investigations at known school gymnasiums and working to characterize the national scope of the problem. This has included contacting flooring manufacturers and performing outreach to states in an effort to identify potential schools that may have these types of floors.

Due to the high degree of variability in the mercury vapor concentrations, it has been difficult to draw conclusions about why some floors emit an unacceptable amount of mercury vapor and some floors do not currently present a health hazard to the children and school staff that use them. Rather than create further uncertainty or panic about the hazards of these flooring materials, the objective of ATSDR’s collaborative work is to provide more detailed information that would enable local school authorities to make informed risk management decisions about their facilities and to provide parents and students with appropriate public health information.

The purpose of this paper is to examine the gas-phase mercury concentration data that has been collected from school gymnasiums, analyze data taken during small-scale chamber tests of samples of the flooring material, and compare the results in order to better characterize the nature of these mercury emissions. It is anticipated that the insights gained can be used to address this developing public health issue.

2. Field Data Measurements

2.1 Field Data Objectives

The overall objective of this paper is to determine if chamber tests can adequately emulate mercury emissions in school gymnasiums, and using the results of the laboratory experiments, determine what factors control emissions. There are several sub-objectives associated with this overall objective:

- 2.1.1 First, in order to evaluate the health threat from the mercury exposure, gas-phase mercury concentrations in the gymnasium breathing zone must be characterized.
- 2.1.2 The second sub-objective is to determine if ‘hot spots’ (for example, where holes were placed in the floors to hold equipment) represent a health concern and if damaged floors represent a greater risk than undamaged floors.
- 2.1.3 The third sub-objective relates to the mercury emission rates: can the emission rates be characterized, and what is the range of rates? Also, is the emission rate related to the year that the gymnasium floor was installed?

2.2 Gas-Phase Mercury Concentrations

To accomplish the objectives of this thesis, gas-phase mercury concentrations were collected from 57 different school gymnasiums as shown in Table 1. The concentrations were measured and recorded using handheld devices, such as Jerome meters or Lumex samplers. While most of the data were collected by state health department staff in partnership with ATSDR, some data was provided to ATSDR upon request. The earliest sampling was performed in 2002, while the latest results were collected in the summer of 2009. A total of 67 different sampling events were recorded, but some were conducted on different dates at the same school. In two cases, the same school had two different samples taken on the same day, because the school had two separate gymnasiums with mercury laden floors. As shown in Table 1, the names of the schools have been replaced by numbers to maintain confidentiality.

Table 1 – Measured Mercury Concentrations from Selected School Gym Floors

<i>School</i>	<i>Date</i>	<i>Air Temp (°F)</i>	<i>Max (ng/m³)</i>	<i>Min (ng/m³)</i>	<i>Avg (ng/m³)</i>
<i>1</i>	1-Feb-06		7200	350	1328
<i>1</i>	7-Feb-06		1200	39	527
<i>2</i>	1-Feb-06		550	170	339
<i>2</i>	7-Feb-06		3100	141	394
<i>3</i>	9-Mar-06	68	3400	24	1871

3	16-Mar-06	74	656	844	739
4	11-Mar-04	70	249	50	183
5	9-Mar-06	71	18	11	16
6	9-Mar-06	71	111	105	108
7	9-Mar-06	71	1500	386	1184
8	1-Jun-06	78	8700	2900	5800
8	5-Jun-07	74	2800	1500	1821
9	21-May-07	70	0	0	0
10	15-Feb-07	70	6	13	10
11	15-Feb-07	66	16	27	21.3
12	15-Feb-07	64	15	9	12
13	15-Feb-07	64	24	15	19
14	15-Feb-07	64	12	9	10
15	15-Feb-07	64	21	12	16
16	13-Feb-07	81	24	9	12
17	6-Feb-07	70	730	241	555
18	16-Feb-07	68	1300	100	428
19	20-Feb-07	68	1000	700	771
20	23-Feb-07		0	0	0
21	5-Mar-07		0	0	0
22	5-Mar-07	66	135	102	116
23	5-Mar-07	70	14	8	11
24	13-Feb-07	68	9	6	7
25	12-Feb-07	61	18	15	16
26	29-Jan-07	52	700	700	700
26	29-Jan-07	60	1000	300	495
27	22-Jan-09		6100	157	666
28	7-Jul-04		42,300		420
28	7-Jul-04		2500		700
29	22-Aug-02		77,190		130
30	4-Apr-05		3208		700
31	21-Oct-04				1369
31	29-Oct-04				319
32	6-Apr-05		12,000		2900
33	25-May-06	71			2699
33	9-Jun-06	76			2534
33	16-Jun-09	77			434
33	30-Jun-09	75			553
34	1-Jun-02		1500	1600	1550
35	1-Jun-02		1400	1600	1500
36	1-Jun-02		790	940	865
37	1-Jun-02		860	1650	1255
38	15-Oct-09		2219	365	1168
39	25-Jan-06	66	480	426	461
40	25-Jan-06	69	301	268	285
41	25-Jan-06		370	270	333

42	25-Jan-06		250	237	241
43	25-Jan-06	67	237	174	213
44	14-Feb-06	67	148	106	130
45	14-Feb-06	66	281	214	243
46	14-Feb-06	67	377	265	339
47	15-Feb-06	62	96	38	72
48	14-Feb-06	62	135	73	112
49	13-Feb-06	66	227	87	151
50	14-Feb-06	65	772	636	696
51	15-Feb-06	68	181	115	158
52	14-Feb-06	63	677	516	622
53	14-Feb-06	60	109	87	97
54	14-Feb-06	67	306	260	272
55	5-May-07		710	220	465
56	6-Jun-07	69	800	300	550
57	1-Jun-07	77	10,050	3472	6761
<i>Average</i>					738
Average based on values above screening level of 200 ng/m³ (highlighted in yellow)					1118

The first sub-objective is to characterize the mercury concentrations in the breathing zone, in order to evaluate the health threat from these mercury volatilization exposures. This was accomplished by compiling the mercury concentration data from the 57 schools and evaluating the data using health-based guidelines. The maximum, minimum and average readings in Table 1 are for mercury concentration levels in the breathing zone, as measured by handheld devices. All of the measured mercury values are assumed to be elemental mercury, as opposed to organic mercury compounds. This assumption is based on a study conducted by Beaulieu et al. (2008).

In general, inhalation of high doses of elemental mercury can cause permanent neurological damage and negatively affect the brain. It can also severely impact the kidneys during both acute and chronic exposures. Short term effects from exposure to mercury vapor can include damage to the lining of the mouth and lungs, nausea, vomiting, diarrhea, increases in blood pressure or heart rate, skin rashes, and eye irritation (ATSDR 1999). ATSDR recommends isolating residents from exposure to mercury at a value of 10,000 ng/m³ (ATSDR 2006a). The average mercury levels shown in Table 1 do not approach concentrations that cause acute deleterious effects. For screening purposes, ATSDR uses a value of 200 ng/m³; readings below this screening value are not considered further, while readings above the value will continue to be evaluated. There is no indication of inherent risk in the screening value. Values above the screening value are highlighted in yellow on Table 1; the average mercury concentration was 740 ng/m³, which increased to 1100 ng/m³ after those values below the screening value were excluded from the averaging. ATSDR recommends that breathing zone concentrations should not exceed 1,000 ng/m³ for longer term exposures such as in a residential setting, while 3,000 ng/m³ is considered a safe level for adults and children who are exposed up to a maximum of 40 hours per week. Since these are school gymnasiums where students would not be expected to spend a significant amount of time, this value can be used as a conservative guideline. The California Office of Environmental Health Hazard Assessment uses a value of 1,800 ng/m³ for chronic inhalation to mercury vapors (COEHHA 2004). From Table 1, 14 school floors had

average readings above the residential ATSDR level (25%), and 7 had average readings above the California level (12%), while only 2 schools had average mercury concentrations above the ATSDR 40 hours per day level of 3,000 ng/m³. This does not indicate that there are harmful effects at these schools, but that a health agency, such as the state health department, should follow-up with the school, as was done for all the schools listed in Table 1. This sub-objective was met by evaluating the data using established health guidelines; one quarter of the schools measured would need further evaluation by a health agency, based on readings taken in the breathing zone.

The second sub-objective is to determine if ‘hot spots’ and damaged areas represent a health concern. As mentioned, ATSDR recommends isolating residents from exposure to mercury at a value of 10,000 ng/m³. As shown in Table 1, only 4 of the 57 schools (schools 28, 29, 32 and 57) had a measured concentration above 10,000 ng/m³, and these were all from single sources such as a hole placed in the floor for a volleyball pole, and not an average across a gymnasium. Additionally, the sample was taken at the surface of the floor using the handheld measuring device, and not from the breathing zone. These exposures would not be considered significant since a child would not be expected to breathe directly from air in the hole. Therefore, it can be determined that only 7% of the schools measured had problems with hot spots, and using health-based guidelines, these would not be considered significant, although it would be prudent to continue monitoring them until mitigation takes place.

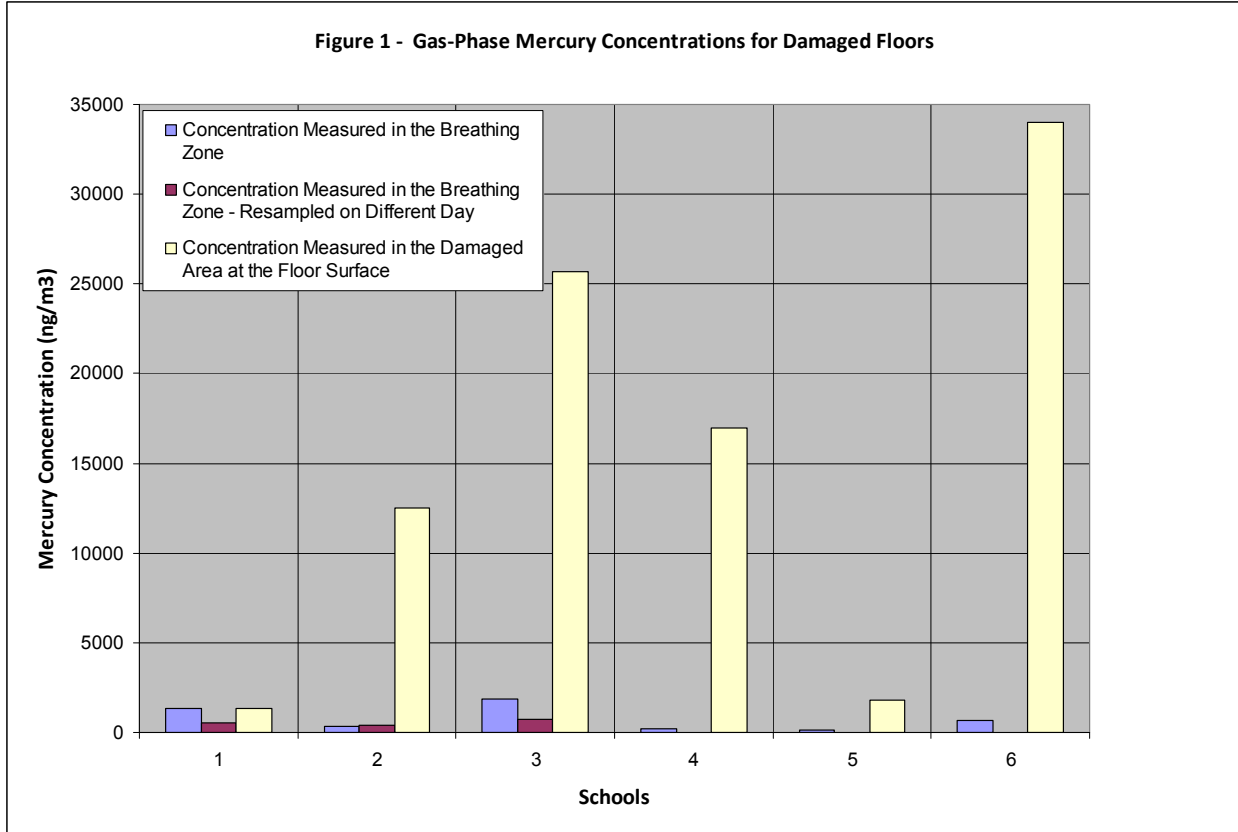
Table 2 – Measured Mercury Concentrations from Damaged Areas of School Gym Floors

<i>School</i>	Date	Concentrations Taken in the Breathing Zone Avg (ng/m ³)	Measured Concentrations Taken at the Floor Surface		
			Max (ng/m ³)	Min (ng/m ³)	Avg (ng/m ³)
1	7-Feb-06	527	1300		1300
2	1-Feb-06	339	19000	8600	12533
3*	9-Mar-06	1871	32000	16000	25667
3*	16-Mar-06	739	14000		14000
4	11-Mar-04	183	17000	2900	
22	5-Mar-07	116	3000	646	1823
27	7-Aug-09	176	34000	2600	
Average					11065

It is also important to determine if damaged floors represent a greater risk than intact floors. While Table 1 provides data from intact flooring, Table 2 lists maximum, minimum and averaged readings from damaged flooring. These are areas on the flooring where the surface was cut or torn, exposing inner regions of the flooring. In the majority of cases with torn flooring, the data readings are much higher, but not in all cases. Six of the 57 schools had areas of damaged flooring, and Table 2 displays this data. School 3 was sampled twice, a week apart, with lower mercury concentrations obtained during the second sampling event, even with a higher temperature the second day (14,000 vs. 26,000 average mercury of ng/m³). This was likely due to the HVAC system running during the second sampling event, providing additional

air flow to dilute the mercury vapors. The average readings are all highlighted since they are all above the screening value of 200 ng/m^3 . As shown, most of these values were above the referenced health-based guidelines. It should be noted again that these measurements were taken at the flooring surface at the specific damaged areas of the floor. As shown in Table 2, the corresponding average breathing zone mercury concentrations are also provided. The average mercury concentration from the damaged flooring was $11,000 \text{ ng/m}^3$, almost 10 times as high as those values from undamaged flooring, and above the acute guideline of $10,000 \text{ ng/m}^3$.

The dramatic differences between breathing zone concentrations from undamaged flooring and gas-phase sample results from the surface area of the damaged floor can be seen in Figure 1. The breathing zone mercury concentrations are taken from data presented in Table 1, while those gas-phase concentrations from damaged surface areas are taken from data in Table 2. Schools 1 through 4 are listed correctly; however Schools 5 and 6 on Figure 3 represent schools 22 and 27 from Tables 1 and 2, respectively. To illustrate, School 3 had an average mercury concentration of 1900 ng/m^3 based on sampling from March 9, 2006; and a concentration of 740 ng/m^3 from a week later. However, a damaged area of the same floor, based on March 9 sampling, had a much higher average concentration of $26,000 \text{ ng/m}^3$. It must be stated, in general, that during sampling events, scratched, torn or otherwise marred sections of flooring were occasionally seen and usually sampled at the flooring surface, and many of these were not found to have significantly increased mercury concentrations and therefore were not recorded. Only the six schools shown in Table 2 had logged increased values for mercury. However, the graphical analysis in Figure 1 clearly shows that mercury concentrations from the damaged floors are significantly higher than those from intact flooring, indicating that the damaged floors do indeed represent a greater concern than intact floors, and that these schools do need to be closely monitored. However, since the measured readings were from single specific sources and not breathing zone averages taken across the whole gym, immediate actions are not needed.



2.3 Emission Rate

The next sub-objective is to characterize the emission rates and determine if mercury emissions in school gymnasiums are comparable to those measured in laboratory chambers. The average emission rate is calculated from these readings, using the formula $E = yQ/A$, where E is the emission rate in $\mu\text{g}/\text{m}^2\text{s}$, y is the mercury concentration in ng/m^3 , Q is the air flow of 2100 feet³/minute or cfm) and A is the area in square feet. This rate is based on the average y values and uses the actual square footage of the gymnasium when available. The HVAC (Heating, Ventilation and Air Conditioning) flowrate was not available from most of the schools during testing. Only one gymnasium had a measured air flowrate (school 18 – 2100 cfm), so this value has been used as an assumption throughout the calculations. Air temperature is also provided, since it has been shown that temperature has a direct affect on mercury emission rates. All the temperatures are in the range of what can be considered normal room temperatures. In fact, it was shown in work performed by the Minnesota Department of Health that the mercury emission rate doubles with each 9° F (5° C) increase in temperature (ATSDR 2008).

Table 3 – Measured Mercury Concentrations from Selected School Gyms with Known Surface Area

<i>School</i>	<i>Date</i>	<i>Max (ng/m³)</i>	<i>Min (ng/m³)</i>	<i>Avg (ng/m³)</i>	<i>Air Temp (°F)</i>	<i>Surface Area of floor (Sq Ft)</i>	<i>Avg Emission Rate (intact floor, ug/m²s)</i>
8	1-Jun-06	8700	2900	5800	78	7549	8.19E-03
8	5-Jun-07	2800	1500	1821	74	7549	2.57E-03
10	15-Feb-07	6	13	10	70	8000	1.32E-05
11	15-Feb-07	16	27	21.3	66	2870	7.91E-05
12	15-Feb-07	15	9	12	64	2460	5.33E-05
13	15-Feb-07	24	15	19	64	2870	7.21E-05
14	15-Feb-07	12	9	10	64	5100	2.17E-05
15	15-Feb-07	21	12	16	64	2583	6.65E-05
16	13-Feb-07	24	9	12	81	3500	3.64E-05
17	6-Feb-07	730	241	555	70	5760	1.03E-03
18	16-Feb-07	1300	100	428	68	9216	4.95E-04
19	20-Feb-07	1000	700	771	68	7992	1.03E-03
22	5-Mar-07	135	102	116	66	36,000	3.44E-05
24	13-Feb-07	9	6	7	68	4485	1.62E-05
26	29-Jan-07	700	700	700	52	7000	1.07E-03
26	29-Jan-07	1000	300	495	60	7000	7.54E-04
27	22-Jan-09	6100	157	666		60,000	1.18E-04
33	25-May-06			2699	71	45,000	6.40E-04
33	9-Jun-06			2534	76	45,000	6.01E-04
33	16-Jun-09			434	77	45,000	1.03E-04
33	30-Jun-09			553	75	45,000	1.31E-04
38	15-Oct-09	2219	365	1168		3200	3.89E-03
TOTAL						12,564	9.55E-04

Values in red calculated from assumed flowrate Green is average surface area

highlighted values above screening level of 200 ng/m³ yield an emission rate of 1.59E-03

Excluding those values of zero, the emission rates ranged from 1.3E-05 (school 10) to 8.2E-03 (school 8) ug/m²s, as shown in Table 3. The average value obtained for the emission rate, 9.6E-04 ug/m²s, was based on those readings from school gymnasiums where the surface area was actually known, leaving the air flowrate as the only assumption. Additionally, when those mercury readings listed in Table 3 that are below the ATSDR screening value of 200 ng/m³ (highlighted) are removed from the averaging, a mean emission rate of 1.6E-03 ug/m²s is obtained.

Several average emission rates were also calculated using a range of assumed flowrates, and these are shown in Table 4. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) has established minimum air flowrate standards for public buildings, using 3 cfm/100 ft². For a school gymnasium with a surface area of 60,000 ft², this would equate to a flowrate of 1800 cfm, which is used as the lower range minimum in Table 4 (ASHRAE 2010). The 2100 cfm assumed flowrate from Table 3 is also displayed on Table 4. Since the air exchange rates in buildings are commonly set at 0.1 to 0.2 changes per hour, the upper flowrate range limit was calculated using 0.2 air changes per hour in the formula N =

60Q/V, which provided a flowrate of 4000 cfm. This results in a range of emission rates of 8.2E-04 to 1.8E-03 ug/m²s (1.4E-03 to 3E-03 ug/m²s when screened using the 200 ng/m³ guideline, as highlighted).

Table 4 – Calculated Emission Rates Based on Assumed Flowrates from Selected School Gyms with Known Surface Area

School	Date	Average Mercury Reading (ng/m ³)	Surface Area of floor (Sq Ft)	Average Emission Rates (ug/m ² s) Based on Assumed Flowrates			Mean Emission Rate Based on the Range of Flowrates
				Avg Emission Rate using Flowrate of 1800 cfm	Avg Emission Rate using Flowrate of 2100 cfm	Avg Emission Rate using Flowrate of 4000 cfm	
8	1-Jun-06	5800	7549	7.02E-03	8.19E-03	1.56E-02	1.13E-02
8	5-Jun-07	1821	7549	2.20E-03	2.57E-03	4.90E-03	3.55E-03
10	15-Feb-07	10	8000	1.14E-05	1.32E-05	2.54E-05	1.84E-05
11	15-Feb-07	21.3	2870	6.78E-05	7.91E-05	1.51E-04	1.09E-04
12	15-Feb-07	12	2460	4.46E-05	5.33E-05	9.91E-05	7.18E-05
13	15-Feb-07	19	2870	6.05E-05	7.21E-05	1.34E-04	9.75E-05
14	15-Feb-07	10	5100	1.79E-05	2.17E-05	3.98E-05	2.89E-05
15	15-Feb-07	16	2583	5.66E-05	6.65E-05	1.26E-04	9.12E-05
16	13-Feb-07	12	3500	3.13E-05	3.64E-05	6.96E-05	5.05E-05
17	6-Feb-07	555	5760	8.81E-04	1.03E-03	1.96E-03	1.42E-03
18	16-Feb-07	428	9216	4.25E-04	4.95E-04	9.43E-04	6.84E-04
19	20-Feb-07	771	7992	8.82E-04	1.03E-03	1.96E-03	1.42E-03
22	5-Mar-07	116	36,000	2.95E-05	3.44E-05	6.55E-05	4.75E-05
24	13-Feb-07	7	4485	1.43E-05	1.62E-05	3.17E-05	2.30E-05
26	29-Jan-07	700	7000	9.14E-04	1.07E-03	2.03E-03	1.47E-03
26	29-Jan-07	495	7000	6.46E-04	7.54E-04	1.44E-03	1.04E-03
27	22-Jan-09	666	60,000	1.01E-04	1.18E-04	2.25E-04	1.63E-04
33	25-May-06	2699	45,000	5.48E-04	6.40E-04	1.22E-03	8.83E-04
33	9-Jun-06	2534	45,000	5.15E-04	6.01E-04	1.14E-03	8.29E-04
33	16-Jun-09	434	45,000	8.82E-05	1.03E-04	1.96E-04	1.42E-04
33	30-Jun-09	553	45,000	1.12E-04	1.31E-04	2.50E-04	1.81E-04
38	15-Oct-09	1168	3200	3.34E-03	3.89E-03	7.41E-03	5.38E-03
TOTAL				8.19E-04	9.55E-04	1.82E-03	1.32E-03
highlighted values above screening level of 200 ng/m³ yield an emission rate of:				1.36E-03	1.59E-03	3.02E-03	2.19E-03

The range of mercury emission rates from Table 3 is presented in Figure 2. The majority of the emission rate values range from close to zero to 3.9E-03. In general, the emission rates can easily be calculated from the gas-phase mercury concentrations, and should be an effective comparison tool in the evaluation between the mercury emissions in school gymnasiums and the measured rates from the chamber test experiments.

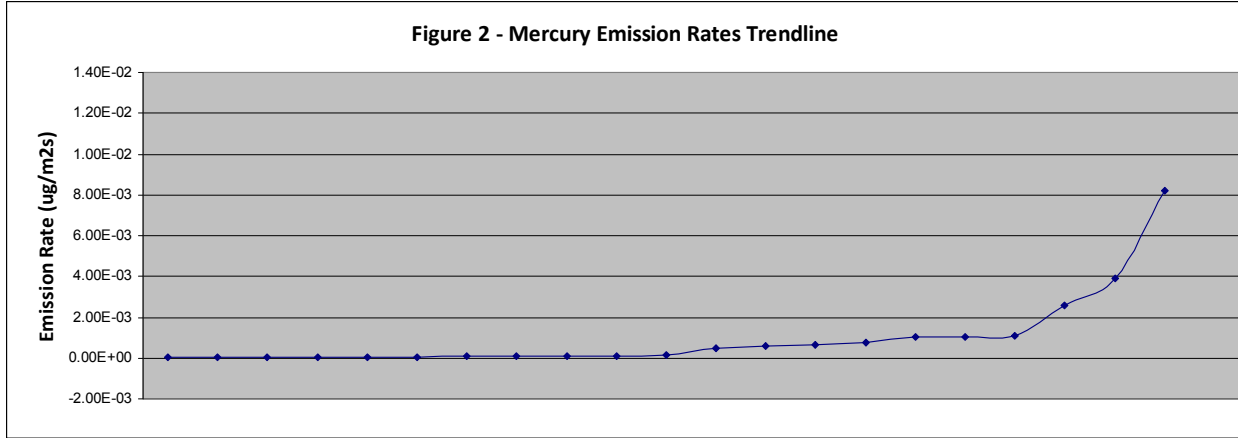
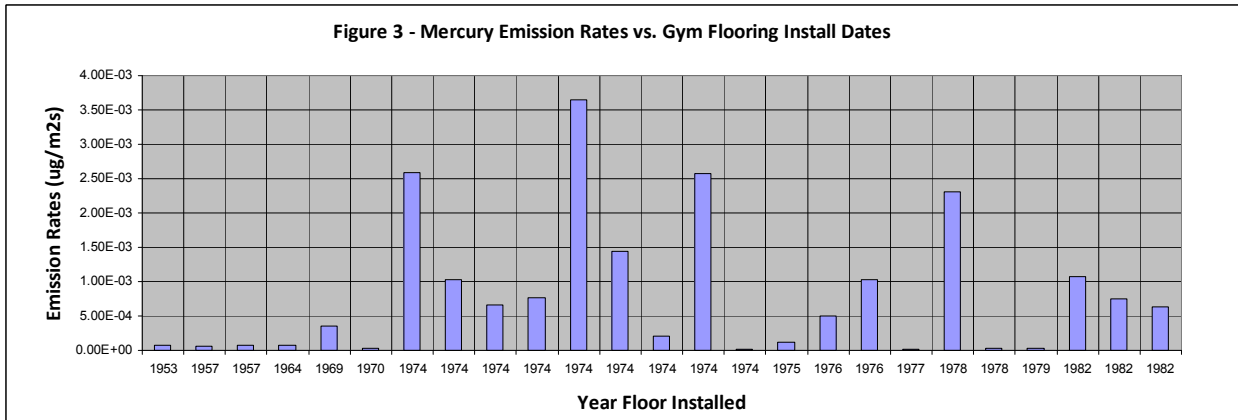


Figure 3 charts the year that specific floors were installed versus the emission rate of that particular floor. The purpose of the figure is to determine if a trend can be seen when comparing the year a gymnasium floor was installed to the associated emission rate. As the figure shows, there is no discernable trend. Based on the 25 schools where the installation date was known, several specific years had clusters of higher emission rates (e.g. 1974), but a correlation with time was not observed. Therefore, it was determined that the age of the flooring does not correlate to emission rates.



3 Chamber Testing

3.1 Chamber Testing Objectives

Several data gaps exist in the evaluation of mercury contaminated gymnasium floors. To help fill these data gaps, and to gain some insight into the behavior of these mercury emitting floors, a series of chamber tests was performed on samples of flooring. The purpose of the chamber testing is to measure emission rates for various configurations, devised to emulate a school gymnasium, to see if a laboratory setting can be used to estimate emissions from flooring samples taken from gyms. The testing will capture the emission profiles, which can

be compared to each other, but also to aggregated field concentrations. Several sub-objectives must be accomplished in order to meet the overall objective:

- 3.1.1** First, some insight is needed on the nature of the mercury bound within the polymer flooring, and the mechanism for its release. When would steady state concentrations be reached in these experiments?
- 3.1.2** The second sub-objective is to determine if uniformity can be established between sample runs; will the curve profiles be similar, indicating consistent testing methodology? Can these curves be used to determine the mercury degradation rate for a piece of flooring sample?
- 3.1.3** The third sub-objective was to determine if uniformity could be seen between different pieces of material cut from the same source, and between different samples of flooring to determine if a complete different source would still yield similar results.
- 3.1.4** The fourth sub-objective is to determine the effect of temperature on the mercury emission rate.
- 3.1.5** The next sub-objective was to evaluate the inherent degradation rate of the flooring material. This sub-objective involves comparing the 7 liter chamber test to a 36 liter chamber in order to compare the degradation rates.
- 3.1.6** The final sub-objective was to determine if the chamber testing can be configured to simulate a ventilated gymnasium, while obtaining similar results with the expected curve profile of a closed system.

3.2 Materials

In order to meet the overall and sub-objectives for this paper, samples of flooring needed to be obtained for experimentation, and a chamber test had to be designed and prepared to test the flooring samples. The samples of flooring were provided by a college in Michigan, which was replacing the floors in their gymnasium with new surfaces. This involved pulling up and disposing of the old flooring. Multiple samples from the old floor were obtained for research purposes, and cuttings from these samples were placed into chambers for testing. The floor samples were from two separate types of flooring: the first sample was from a green, textured surface that surrounded the basketball court, covering approximately 85% of the gym, while the second sample was a smooth, tan colored cutting from the basketball court itself. Pre-removal Lumex sampling found an average of 170 ng/m³ in the areas with the green flooring, while the air above the tan basketball court measured 320 ng/m³, which rose to a high value of 6100 ng/m³ after being cut for removal. Additionally, the flooring failed the Toxicity Characteristic Leaching Procedure (TCLP) testing, indicating it would need to be disposed in a hazardous waste landfill (ATSDR 2003).

Two chambers were used for all of the experiments; the majority of the testing was conducted in a 7 liter stainless steel chamber with two air portals and a sealable lid, while a few experiments were performed using a similarly constructed chamber with a volume of 36 liters. The samples were placed in the bottom of the chamber on a mesh frame designed to keep the material above the chamber floor, allowing for air flow around the material. Based on past field observations, most wipe samples taken in gyms at the same time as the breathing zone monitoring were non-

detect, therefore it is assumed that all mercury is volatilized and not adhered to the chamber surfaces.

All laboratory measurements were performed using a Lumex RA-915+ Portable Mercury Vapor Analyzer, which was connected directly to the chamber using clear plastic tubing. This channeled the air flow in both types of setups (open and closed system, as illustrated in Figure 4). The closed circuit testing of the chamber, while not allowing fresh air to enter the system, is more useful to investigate the inherent nature of the flooring itself, while the open system is more representative of the conditions of a ventilated school gymnasium.

Figure 4a – Chamber Testing Schematic for Direct Measurement of Mercury Air Concentrations – Open System

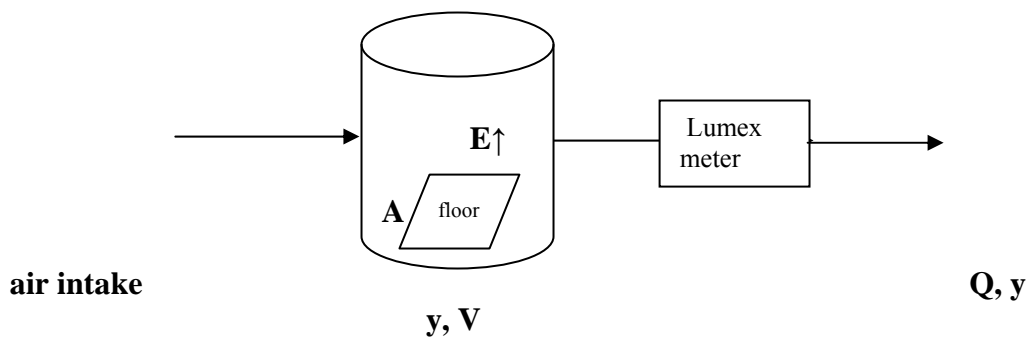
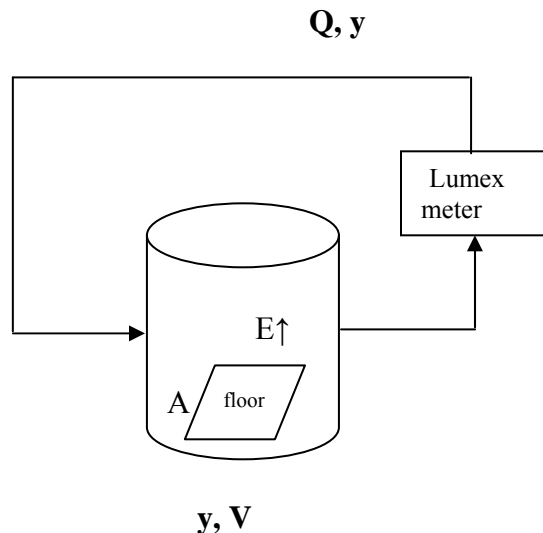


Figure 4b – Chamber Testing Schematic for Direct Measurement of Mercury Air Concentrations – Closed System



- Q = Airflow (ml/min)
- y = Hg Conc (ng/m³)
- T = temp (21° - 31° C)
- V = volume (7 - 36 L)
- A = area of flooring sample (9 in²)
- E = emission rate =

yQ/A ($\mu\text{g}/\text{m}^2\text{s}$)

The internal pump in the Lumex RA-915+ generates the air flow, Q , which ranged from 1.9 to 2.7 liters/minute, as measured by a flow meter prior to each test series. Ambient temperature in the laboratory was a steady 21°C . For those experiments operated at 31°C , the chamber was placed in a temperature controlled cabinet.

The Lumex RA-915+ provides the reading of real time mercury vapor concentrations, with results shown in ng/m^3 . The instrument uses differential atomic absorption spectrometry. A radiation source is placed in a magnetic field and polarized. When mercury atoms are exposed to the field, the difference between the polarized components of the radiation source will increase with the growing mercury vapor concentration. This difference is measured and reported as a concentration. The readings are provided every second, every ten seconds, with an average reading every 30 seconds. In most of the experiments performed as described in this paper, the Lumex was operated in conjunction with a personal computer that logged readings at intervals of a second. The relative deviation value (R %) is also displayed; this reading must be less than 25 to ensure that the instrument is operating properly. The R% value never rose above 25 during any of these experiments, and in fact was generally less than 7. A test was conducted before each operation to check the analyzer's serviceability. The detection limit during standard operation is $2.0\text{ ng}/\text{m}^3$, but the device routinely can measure as low as $0.2\text{ ng}/\text{m}^3$. The upper limit for detection was set at $10,000\text{ ng}/\text{m}^3$ using the set up features on the detector (Lumex 2009).

3.3 Methods

The chamber testing apparatus was arranged as indicated in the Materials subsection. For the first set of experiments, the chamber was configured in a closed system, as shown in Figure 4b. To begin the experiment, a portion of the green spongy flooring, which ambient readings taken in the gymnasium showed to emit less mercury as compared to the tan flooring, was removed from the storage bag, and a small 3 by 3 inch square was cut from this floor sample. This smaller sample, the green cutting, was then allowed to ventilate in a hood for 20 minutes to remove any 'head space' effect. The sample was then placed inside the chamber, using a wire mesh apparatus to hold it vertical, allowing both sides of the piece to be in contact with the air in the chamber. The chamber test temperature remained constant at 21°C and with a flowrate that varied only slightly, ranging from 2.05 – 2.17 liters/minute. The second run of this experiment utilized the same 9 square inch piece of floor sample, at roughly the same flowrate and temperature, and in the same closed circuit chamber experiment, with 15 minutes between the two chamber runs. Five minutes after the second run, a third run was performed exactly the same as the first two. The interval between runs 3 and 4 was fifteen minutes, then ten minutes between 4 and 5. Seven total runs were performed using the closed circuit configuration.

The next experiment was designed to simulate an open gymnasium which would constantly be ventilated. The same green square of material was used, at the same temperature and flowrate, only the chamber test circuit was left open, allowing the chamber to intake air, as depicted in Figure 4a. This particular experiment utilized three runs, with the second and third runs performed the following day.

The following set of experiments was designed to determine the effect of temperature on the mercury emission rate. The green square was again used for this series, only heat was now applied to the same chamber to raise the temperature to 31° C. This was accomplished by placing the chamber in a cabinet where the temperature could be controlled. The flowrate remained constant at 2.10 liters/minute, and the system was set up as in the last experiment, open to atmospheric ventilation. Three runs were performed also for this experiment. Run 1 was terminated at 43 minutes, when the concentration level was at 135 ng/m³ mercury, prior to reaching steady state, while runs 2 and 3 were allowed to reach steady state. On the second run, an initial dip in the plotted line was noted (but very difficult to note graphically). This was likely the Lumex at first measuring the residual mercury in the air left over from the previous run, then as the air flushes with the new sampling, the concentration dropped at first, then climbed as expected. This caused a procedure change in the experiment. In all subsequent experiments, the pump was not shut off between runs but continued to operate, flushing the system of residual mercury. This also allowed for better establishment of a background level to start each successive run.

The next experiment was designed to evaluate the uniformity of different floor cuttings, a second cutting was taken from a different larger sample of floor, but still the same green spongy outer flooring and of a similar size, 9 square inches. This cutting was allowed to ventilate over several days. These experiments duplicated the very first set of experiments, in a closed chamber test system at 21° C. Again, three successive runs were performed.

The purpose of the next set of experiments was to determine if a complete different mercury source would yield similar or contrasting results. A piece of flooring cut from the tan surface on the basketball court was used for this experiment. This piece was also cut into a 3 by 3 inch square, and allowed to ventilate over two days. As noted earlier, field testing of this material indicated a higher mercury concentration than from the green flooring. This experiment duplicated the initial experiment, using a closed chamber test system at 21° C. Three runs were performed. The following experiment also utilized the tan square in one single run, however it was performed at a temperature of 31° C and in an open chamber test.

The final two experiments were designed to evaluate the effect that temperature would have on the steady state concentration in open vs. closed systems. The penultimate experiment utilized a closed chamber test at 31° C. The original green square was again used in this experiment, and two runs were performed. In the final experiment, the 7 liter chamber was replaced by a 36 liter vessel. These two runs were performed at 21° C, using green square 1 again.

For each experiment, a calibration was performed between each run to ensure that the Lumex was working properly. At the very end, a final calibration was done on the Lumex which showed an R% value of 7, well within the acceptable range. Also, handheld operation of the Lumex in the area of the laboratory found an ambient background level of 8 ng/m³ mercury, which was the value generally seen before many of the experiments in the chamber itself.

3.4 General Discussion

The first sub-objective for the chamber testing was to gain some insight on the nature of the mercury bound within the polymer flooring, and determine the mechanism for its release. As mentioned earlier, the flooring was manufactured using phenyl mercuric acetate, or PMA. Although the exact nature of how the PMA molecule is bound within the polymer flooring structure is not well understood, it appears that the molecule is embedded within the polymer strands that make up the foam. The PMA molecule degrades and releases mercury in its elemental form in combination with benzene and acetaldehyde molecules (Beaulieu et al. 2008). After these molecules are released within the polymer strands, they will diffuse to the surface of the strand and then be released into the interior pore spaces of the polyurethane foam. Once they enter the gas-phase within the foam, they quickly diffuse to the exterior surface of the foam material and are released into the ambient air (Zhao et al. 2004). It is therefore thought that there are two steps that limit the rate of release of the mercury from the foam material. The first is the degradation rate of the PMA molecule and the second is the diffusion rate of the mercury within the polymer strands. These chamber test experiments were designed to develop insights into the nature of this process.

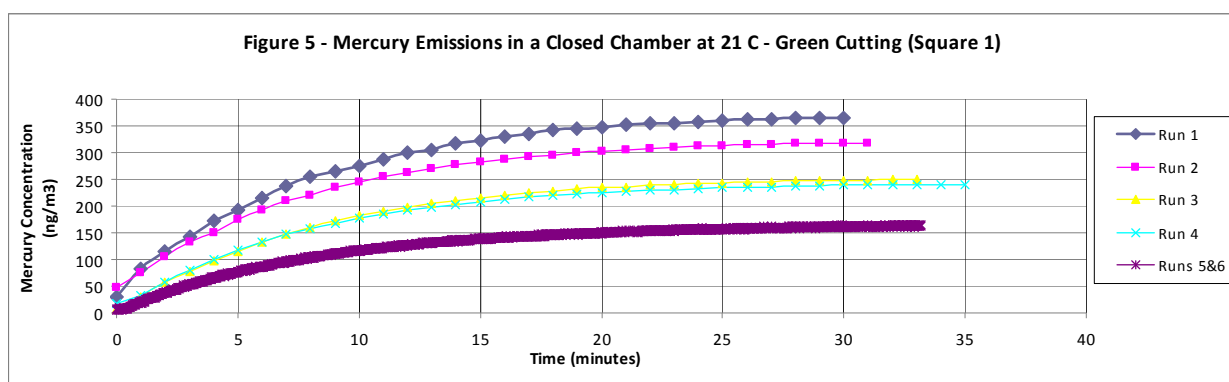
Although it is obvious that the flooring has a finite amount of mercury ingrained in the material, it is unlikely that an experiment would ever exhaust this mercury content. Based on the mercury content within a similar floor, as stated by the manufacturer, the amount of mercury within the 9 square inch sample is estimated to be 1.7E04 ug. Using the degradation rate as specified later in this thesis, it would almost take 1600 years to fully exhaust the amount of mercury in the 9 square inch sample. Furthermore, the observed mercury gas-phase concentrations are well below the vapor pressure. The vapor pressure of a substance is the amount of pressure exerted when the substance is in equilibrium with its own vapor (Nazaroff 2001). Using the vapor pressure of mercury at 21° C [a value of 0.002 mm Hg is obtained from the equation $\log_{10}P = -0.05223a/T + b$, where a is 58,700 and b is 7.752 (Weast 1983)] and the ideal gas law ($PV = nRT$), the mercury gas-phase concentration would be 1.6E08 ng/m³, an extremely high value which assumes the presence of liquid mercury. Thus, if the degradation rate of the PMA molecule is constant, and the foam is in an enclosed space, the mercury molecules can continue to be released from the foam for a long period of time, without approaching the vapor pressure.

High mercury concentrations were measured when the bags were first opened, as high as 20,000 ng/m³ mercury. This is caused by the build up of mercury vapor in the head space of the bag. Since the concentration of the mercury vapor is so much less than the vapor pressure of mercury, this emission process will most likely continue, leading to very high concentrations in the bag. One would also expect a cut in the flooring to release a higher amount of mercury initially than would be expected without cutting. This is because the cutting process exposes fresh surfaces of the polymer strands that have a relatively high concentration of mercury in them near the newly cut surface. Therefore, the samples used in the chamber tests must be given time to ventilate before testing begins.

It is expected that the emission profile (the gas-phase mercury concentration in the chamber as a function of time) will be characterized by an initial rise as the mercury accumulates in the chamber air, followed by a slow leveling off as the system reaches steady state. The second part

of the sub-objective was to determine how long it takes to reach steady state. For the open systems, the steady state condition should be determined by the degradation rate. Under these conditions, the rate at which the mercury is released from the flooring (which equals the degradation rate after a long period of time) is equal to the rate at which it leaves the chamber. For the closed chamber experiments, there will continue to be an increase in concentration that equals the degradation rate, and steady state should never be reached.

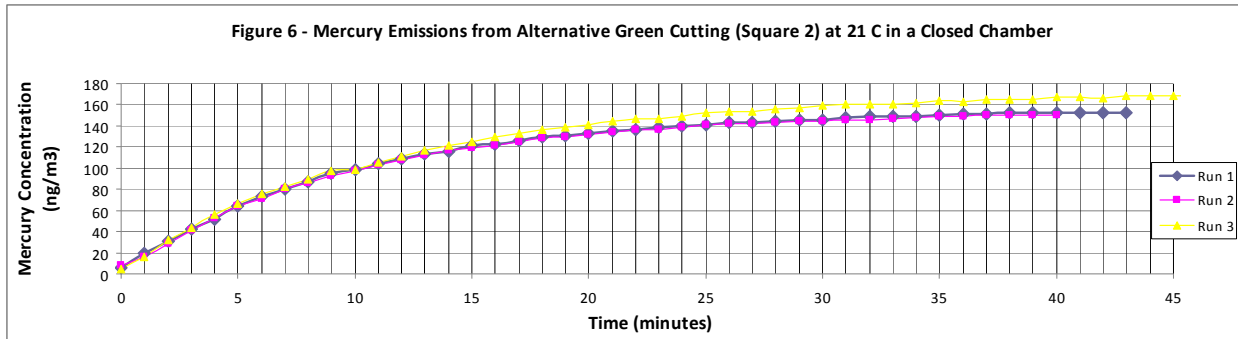
The second sub-objective is to determine if uniformity can be established between sample runs, indicated by similar profiles. Before multiple runs are performed, it needs to be determined if chamber testing is providing consistent results. In order to better prove the methodology, multiple runs with this same experiment using the same cut piece were performed. This experiment, if successful, would also accomplish the second part of this sub-objective, the determination of the degradation rate.



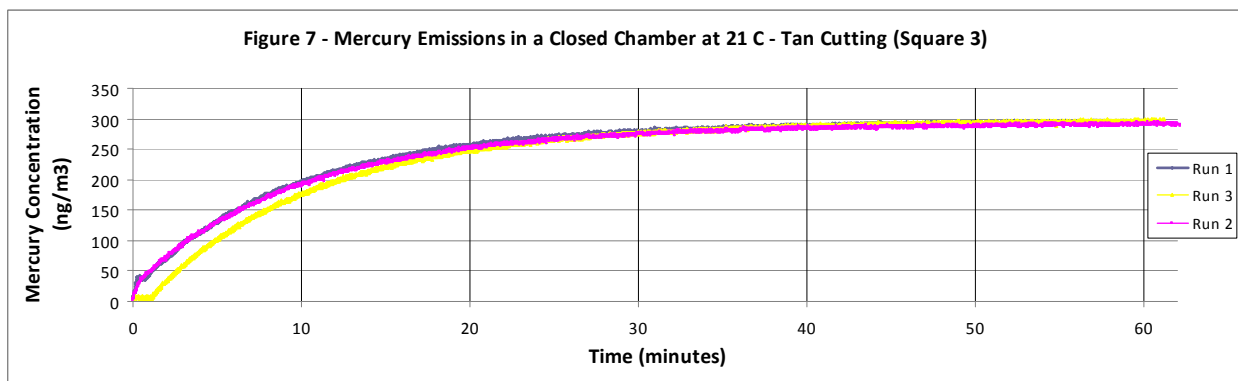
With each successive run, as shown in Figure 5, the mercury concentrations rose more gradually, until runs 5 and 6, which had nearly identical concentration profiles (reaching 163 vs. 165 ng/m³ mercury). This appears to show that during the earlier runs, there was still mercury vapor in the polymer strands that had built up while the flooring was in the bag. After removing the sample from the bag, it took some time for this accumulated mercury to be depleted. Finally, in runs 5 and 6, there is no accumulated mercury and the build up in concentration is only due to the rate at which mercury is being released during the PMA degradation process. This would indicate that this curve (Runs 5 & 6 jointly) represents the degradation rate of the material. This degradation rate can be calculated using the point that the curve levels off at about 30 minutes, which corresponds to an emission rate of 5.4E-05 ug/m²s.

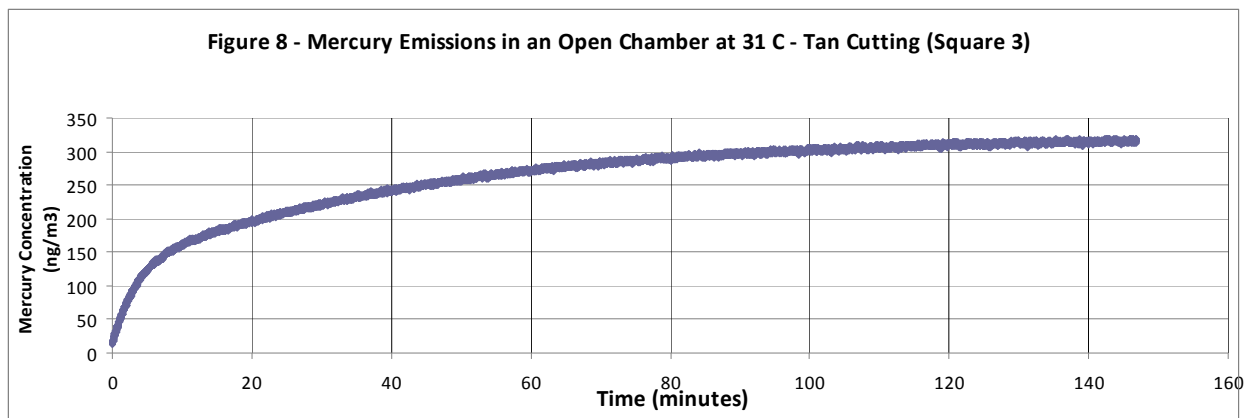
All of the experiments to this point have involved the use of one specific piece of flooring. The third sub-objective was to determine if uniformity could be seen between different pieces of material cut from the same source, the green spongy flooring surrounding the basketball court. The next experiment was designed to evaluate the uniformity of these cuttings, to make sure that different areas of a floor would produce similar mercury emissions. Three runs were performed and very similar results were found. The similarity of the curves is due to the sample being allowed to ventilate in the ambient air for a long time before experimentation, which lowered the accumulated mercury content such that the profiles are controlled by the degradation rate. As shown in Figure 6, the values where the curves leveled off ranged from 150 to 168 ng/m³ mercury, which are very close to Runs 5 & 6 from Figure 5, at 163 ng/m³ mercury. Each of the

three runs was also nearly identical, showing consistency in the methodology and the material's output of emissions. This met the sub-objective of this set of runs, which was to confirm that different cuttings from the same type of material, would yield similar results. To completely confirm this theory, multiple experiments would need to be duplicated and performed.

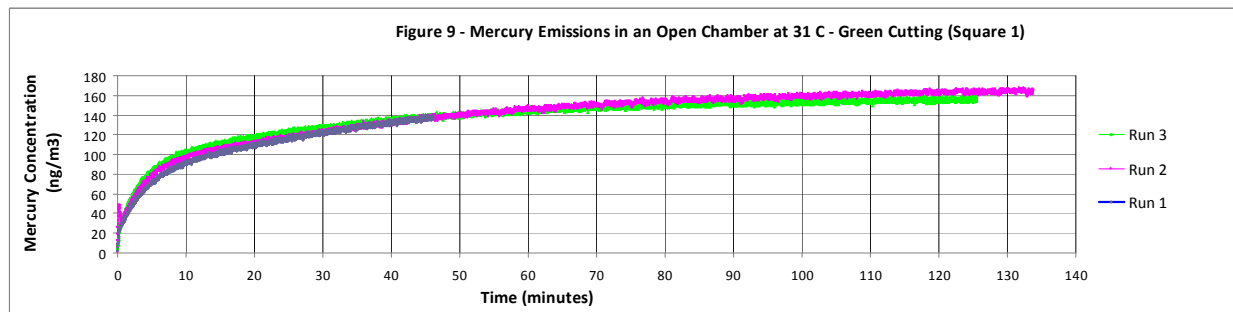


The second part of this sub-objective was to evaluate the tan flooring. As noted earlier, field testing of this material indicated a higher mercury concentration than from the green flooring. Uniformity was seen in each of these runs, as the curve leveled off consistently at 290 – 295 ng/m^3 in one hour (see Figure 7). The purpose of this set of runs was to compare the tan flooring with the green flooring. As expected, the tan flooring did level off at a higher mercury concentration (295 vs. 163 ng/m^3 (from Runs 5 & 6 on Figure 5)). However, these runs took longer when compared to the green flooring. An emission rate for the tan flooring calculated from the plot at the 60 minute point yields $4.9\text{E-}05 \text{ ug/m}^2\text{s}$. The tan square was also used at 31°C in an open chamber test; as compared to the green square in the same experiment, the steady state level of mercury was higher (315 vs. 163 ng/m^3). This higher steady state concentration could also be due to the tan flooring having a higher inherent degradation rate than the green flooring, or a higher concentration of PMA in the material. Figure 8 shows the graphical display of this one single run.



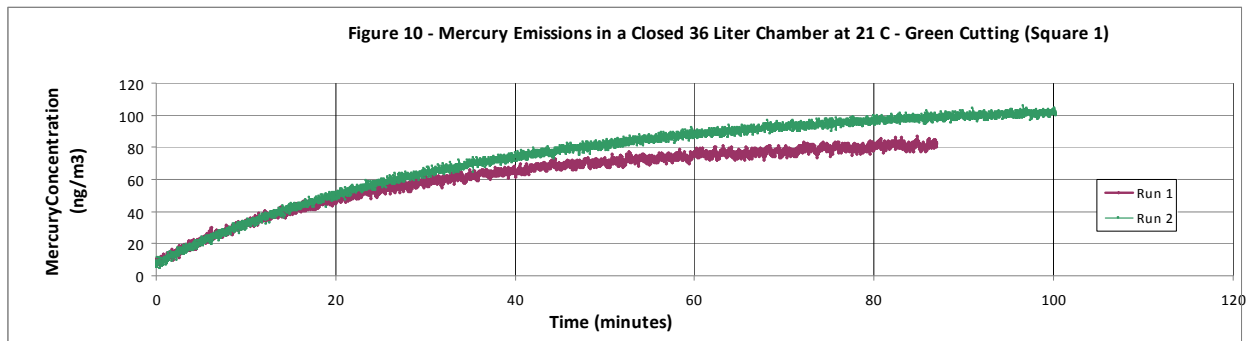


The next sub-objective is to determine the effect of temperature on the mercury emission rate. As shown in Figure 9, steady state was approximated at 163 ng/m³ mercury. Similar to the previous run, since this experiment still used the same cutting, there is very little initial mercury content in the sample, so the profiles are all similar, and based on the degradation rate. However, since the experiment is at a higher temperature, the steady state concentration is higher apparently due to a faster degradation rate. It was expected that the final steady state values would be higher, as the increased temperature could conceivably cause a higher degradation rate of the PMA, which would result in a higher emission rate. This has been seen in actual gymnasiums, as those tested with higher ambient temperatures generally show higher values. As indicated earlier, work performed by the Minnesota Department of Health has indicated that the mercury emission rate doubles with each 9° F increase in temperature. This experiment does document an increase in mercury concentration as expected (72 ng/m³ on Figure 6 vs. 163 ng/m³ on Figure 7). These values correspond to emission rates of 2.2E-04 ug/m²s (at 21° C) vs. 4.9E-04 ug/m²s (at 31° C), an increase of 220%. These calculations are based on the actual measured flowrate and surface area in the chamber. In all, the sub-objective for this particular experiment, to determine what effect temperature will have on the mercury emission rate, was met, as the emission rate was shown to more than double with a 10° C increase in temperature.



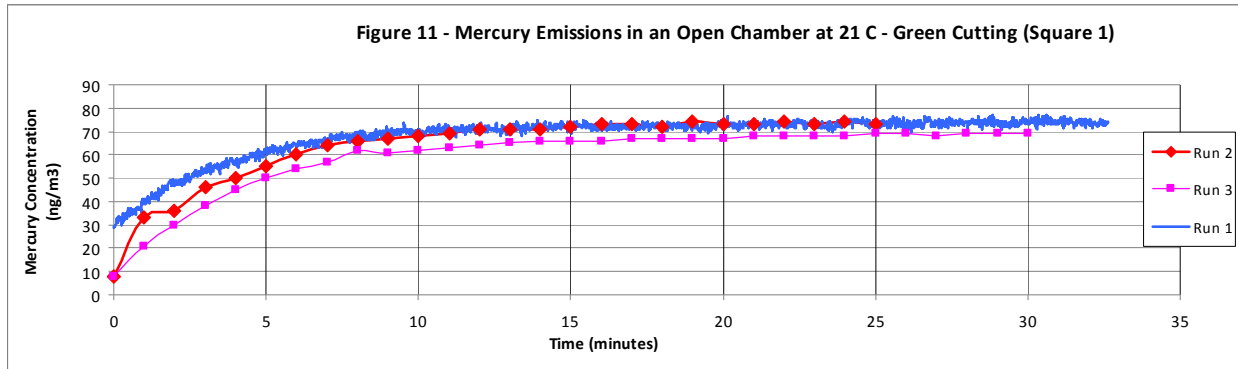
The fifth sub-objective was to evaluate the inherent degradation rate of the flooring material. In order to gain some insight on this sub-objective, degradation rates were compared between the 7 liter chamber test and a 36 liter chamber. The larger chamber provides an increased amount of air in the closed system, and will provide different mercury concentrations versus the 7 liter chamber. During experimentation, the 36 liter test leveled out at 1.3 hours, reaching 80 ng/m³ of mercury. This test was repeated in a second run, which leveled off in 1.7 hours, with a

concentration of 100 ng/m^3 mercury (Figure 10 shows both runs graphically). These runs are compared to the 7 liter chamber test, which took 30 minutes on average to level off. However, it would be expected that the degradation rate, inherent to the material, should be the same in the large vs. small chambers. When the emission rates in both chambers were calculated at the leveling off points, representing the degradation rates, very similar results were found. The degradation rate in the 7 liter chamber, $5.4\text{E-}05 \text{ ug/m}^2\text{s}$, was very close to the rate in the 36 liter chamber, $5.2\text{E-}05 \text{ ug/m}^2\text{s}$, as expected.



The final sub-objective was to determine if the chamber testing can be configured to simulate a ventilated gymnasium. In open chambers, the emission curve can be characterized in two phases, the initial phase based on the build up in mercury in the chamber, and the later phase as the curve approaches the steady state concentration, which is determined by the degradation rate of mercury as it is released from the PMA molecules bound up in the polymer strands of the flooring. The first run of this series approximated steady state in the same amount of time as the closed runs leveled off, only at a lower value (73 ng/m^3 mercury; Run 1 on Figure 11). Later experiments at a higher temperature clearly show the expected effect, with open systems reaching steady state faster than when the closed system levels off. Figure 11 shows the results of the three runs. Runs 2 and 3 were performed two days after initial cutting of the material, so the flooring had clearly been allowed to fully ventilate. As all three of these runs were nearly identical, even though they were not performed in succession, the mercury emission profile of the flooring is fairly consistent. In addition, the first run of this series began with an initial mercury concentration in the chamber of 30 ng/m^3 , while the next two runs had lower initial concentrations at 8 ng/m^3 , but all three had similar ending steady state values, between 69 and 73 ng/m^3 (72 ng/m^3 average). Based on Figure 11, at the 10 minute mark, the mercury concentration of 70 ng/m^3 corresponds to an emission rate of $7\text{E-}05 \text{ ug/m}^2\text{s}$. This would be the transition point from initial mercury content to degradation rate. After this point, the curves are more based on the degradation rate. Additionally, at the 10 minute mark, based on a 7 liter chamber, 3 residence times have been allowed to occur with a flowrate of 2.1 liters/minute. As the chamber becomes well-mixed, the initial increases level off. At 25 minutes, when the curve indicates steady state, an emission rate can be calculated at $2.9\text{E-}05 \text{ ug/m}^2\text{s}$, which would equal the degradation rate. In comparison to a closed system, using Figure 5, the transition point could be estimated to occur at 15 minutes, which corresponds to an emission rate of $9.4\text{E-}05$, slightly higher than the open system's transition point. Also, the point that the curve levels off, 30 minutes, would correspond to an emission rate of $5.4\text{E-}05 \text{ ug/m}^2\text{s}$, somewhat higher than the open system's degradation rate of $2.9\text{E-}05 \text{ ug/m}^2\text{s}$, but less so when considering that the closed system's 'leveling off' concentration will only slightly increase over a large time. In fact, an

extrapolated line would show for the curve of Runs 5&6 167 ng/m^3 at 40 minutes, an emission rate of $4.2\text{E-}05 \text{ ug/m}^2\text{s}$, which in theory should continue to decrease over time until it reaches the open system's degradation rate of $2.9\text{E-}05 \text{ ug/m}^2\text{s}$.



4 Results and Overall Discussion

The overall objective of this paper was to determine if chamber testing can adequately emulate mercury emissions in school gymnasiums. The chamber tests ran at 21°C in an open system would come closest to simulating a gymnasium, as the average temperature was 68°F (20°C). For the green flooring, Figure 11 represents chamber testing at 21°C in an open system, where a steady state emission rate of $2.9\text{E-}05 \text{ ug/m}^2\text{s}$ was calculated. For the tan flooring, tests were only performed in a closed system, however Figure 7 clearly shows a leveling off point at 60 minutes for the 21°C of the tan flooring. An emission rate at this point would be $4.9\text{E-}05 \text{ ug/m}^2\text{s}$. Since the green flooring covers 85% of the gym, using 85% of the emission rate from Figure 11 ($2.9\text{E-}05 \text{ ug/m}^2\text{s}$) plus 15% of the emission rate from Figure 7 ($4.9\text{E-}05 \text{ ug/m}^2\text{s}$), an emission rate based on laboratory data would be $3.2\text{E-}05 \text{ ug/m}^2\text{s}$. In the actual gymnasium where the floor samples were obtained, the average mercury concentration in the breathing zone was 170 ng/m^3 . The emission rate calculated from this concentration would be $3.1\text{E-}05 \text{ ug/m}^2\text{s}$, extremely close to the laboratory emission rate of $3.2\text{E-}05 \text{ ug/m}^2\text{s}$. This would indicate that the laboratory chamber test was successful in emulating the school gymnasium, as the emission rates calculated from the collected data are very comparable. This meets the overall objective of the chamber testing which was to see if floor samples taken from a gymnasium could be measured in the laboratory with similar results to those screened in the actual gym with handheld devices. The data collected in these experiments, although limited in scope, does seem to confirm this.

Many sub-objectives associated with this overall objective were evaluated and accomplished, one set associated with the field data and a second set with the chamber testing. First, for the field data sub-objectives, a range of mercury concentrations in the breathing zone was obtained. Specific 'hot spots' or areas such as where holes were placed in the floors to hold equipment, were evaluated and it was determined that this did not represent a health concern. A second objective determined that damaged floors do represent a greater risk than intact floors, although the overall health threat to the gym is minimal if followed up by a health agency. The next sub-objectives all related to the mercury emission rates and determining if there is a correlation between the year that the gymnasium floor was installed and the magnitude of the associated

emission rate in that gym. A correlation between install date and emission rates was not seen, but the emission rate can be used to evaluate intact flooring vs. damaged floors.

The secondary objective of this paper was to use the results of the laboratory experiments to successfully analyze the emissions curve, determining what factors drive the profile. This objective was met, based on the determination of the two basic phases of the emissions profile, the initial mercury release based on molecules bound within the flooring, and the degradation rate that will take over and control the rate of release. This secondary objective was shown through a set of six sub-objectives related to the chamber testing. The first sub-objective of this second set was to gain some insight on the nature of the mercury bound within the polymer flooring, and the mechanism for its release. Mercury volatilization from the gymnasium flooring is dependent upon the initial amount of mercury released, based on the build up of PMA molecules bound to the polymer strands in the flooring material, and the degradation rate of these molecules as they diffuse through the pore spaces in the polymer flooring, through the surface boundary, and into the ambient air. The vapor pressure of mercury would limit the overall amount of mercury that could be released, but since this value is so high, it is the degradation rate that does the limiting. It is likely that the mercury has built up in the polymer strands to the point where the flooring has a high potential for the release mercury, which would occur at a consistent degradation rate. The second part of this sub-objective was to determine when, in general, the steady state concentration would be reached. In fact, the steady state concentration in closed chambers would likely never be reached, as mercury release would occur over a very long time, and be limited only by the vapor pressure, which is very high. In open chambers, steady state would be reached. This rate of release is in fact the degradation rate. The second sub-objective was to determine if uniformity can be established between sample runs, and in fact the profiles were very similar, indicating consistent testing methodology. The third sub-objective showed uniformity between different pieces of material cut from the same original green flooring and from a second piece of tan flooring. The fourth sub-objective showed that increased temperatures would cause increased mercury emission rates.

The next sub-objective evaluated the inherent degradation rate of the flooring material, utilizing a 7 liter chamber test and a 36 liter chamber in order to compare the degradation rates. The degradation rates in both the smaller and larger chambers were very similar, indicating that the material does have an inherent degradation rate, which can be seen regardless of the size of the chamber. The final sub-objective determined that the chamber testing can be configured to simulate ventilated gymnasiums, as the open chamber testing was used to emulate a ventilated school gymnasium, and leading to the overall objective of the paper.

Finally, what are the practical applications of the findings in this thesis? It was shown that increased temperatures will increase the mercury emission rate, and therefore elevate mercury volatilization from contaminated flooring. This was documented using the open chamber test at 21° C vs. 31° C, which showed an increase in emission rates of 2.2E-04 ug/m²s to 4.9E-04 ug/m²s, more than double. This would lead to the conclusion that air conditioning should be operated in school gymnasiums when temperatures are high, such as in the summer. Also, running HVAC systems in general will reduce mercury levels based on the increased air ventilation. Therefore, schools with polyurethane floors that contain mercury should continue to

operate their ventilation systems and maintain the gymnasiums at moderate temperatures throughout the year to reduce mercury volatilization (ATSDR 2006b, ATSDR 2008).

5 References

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