Tab B

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CPSC Staff Preliminary Evaluation of Drywall Chamber Test Results

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*Due to the interrelated nature of these investigations, these technical reports are being released in draft until the final results from further studies are available for interpretation. These studies are staff level documents and have not yet been reviewed or approved by the agencies participating in this investigatory effort.

Executive Summary

CPSC staff contracted with Lawrence Berkeley National Laboratory (LBL) for measurement of chemical emissions from samples of drywall products obtained as part of the investigation of imported (Chinese) drywall.

The purpose of this preliminary evaluation was to evaluate chemical emissions from Chinese drywall and from drywall from others sources (in this report, non-Chinese drywall is referred to as North American or NA), the possible differences in chemical emissions between the two sources of drywall products, and the possible chemical exposures in homes that contain either of these two sources of drywall.

The Lawrence Berkeley National Laboratory (LBL) data contained measures for a number of compounds presented in four chemical/chemical subgroups, including: total volatile organic compounds (TVOCs), total volatile sulfur compounds (TVSCs), formaldehyde, and acetaldehyde.

No discernible differences in chemical emissions were noted between drywall products from China and from other sources, except for total volatile sulfur compounds (TVSCs). Mean TVSC emission rates were 12.1 μg/m^2/hr and 0.5 μg/m^2/hr for Chinese and NA drywall, respectively. Emissions of total volatile organic compounds (TVOCs)—ranging from about 6.1 μg/m^2/hr to 119.6 μg/m^2/hr—and for formaldehyde—ranging from 4.6 μg/m^2/hr to 15.88 μg/m^2/hr—were not dissimilar from other studies of chemical emissions from drywall. Mean emission rates for TVOCs were 29.5 μg/m^2/hr (Chinese) and 36.6 μg/m^2/hr (NA), and 6.1 μg/m^2/hr (Chinese) and 8.3 μg/m^2/hr (NA) for formaldehyde. The results reported by LBL are consistent with TVOC and formaldehyde emission rates for drywall observed in the other studies.

The staff used the reported emission factors in a computer model to estimate the concentrations of the chemicals in the indoor air of a home that might result from the presence of the product. Because of the preliminary status of the data, a simple one-zone model was used. The model accounted for factors, such as air exchange rate and room volume, that impact the concentrations of chemicals in the indoor air. The model did not include sink effects; *i.e.*, the effects of various conditions and contents of a room through which chemicals may be removed from the air due to adsorption or absorption onto articles in the room, such as furniture and carpeting. The lack of sink effects in the model likely results in estimates that are conservative and higher than what would be encountered in an actual occupied home environment that would typically include sinks.

The mean concentrations in indoor air for the four chemical classes were calculated for NA and Chinese drywall. The largest apparent difference between the two sources of drywall product is seen in the emission factors and estimated residential indoor air concentration for TVSCs. The estimated concentrations of these compounds for the Chinese drywall (mean 96.7 μg/m^3; standard deviation 135.1 μg/m^3) were considerably higher than the concentrations of TVSCs estimated for the NA drywall (mean 4.3 μg/m^3; standard deviation 3.3 μg/m^3). Of note is that the first five Chinese drywall samples examined in the LBL chamber study were found, in a separate laboratory study, to have high levels of elemental sulfur, relative to North American drywall samples (see statistical analysis of elemental analysis report by Garland and Greene, 2009).

Furthermore, the samples with the highest levels of elemental sulfur in that study correspond to the samples designated as C1, C3, and C4 in the current preliminary drywall emissions evaluation.

On the other hand, the mean estimated air concentrations of acetaldehyde and formaldehyde (6.7 µg/m^3 and 66.5 µg/m^3, respectively) were somewhat higher for the NA drywall samples than the estimates for Chinese drywall (4.0 µg/m^3 and 49 µg/m^3). Similarly, the concentrations of TVOCs were higher for the NA drywall (mean 292 µg/m^3) compared to the Chinese samples (mean 236 µg/m^3).

This preliminary evaluation does not take into account all the expected complexity of an exposure assessment. For example, certain factors that might be expected to significantly influence the assessment, such as modeling sink effects, were not included. Further, this work has not quantified all possible chemicals of interest, and staff has not taken into account other factors that could result in higher or lower estimates of indoor air concentrations. As with any model-based exposure assessment, there are numerous assumptions, limitations, and sources of uncertainty that should be explored further. Thus, this evaluation will be followed by a more comprehensive exposure study once additional data become available.

While, the data provided by LBL to date are limited, and the sample size is small, these data provide important information about chemicals that may be emitted from Chinese drywall products that are not also released from NA drywall. Based on these preliminary results, the most salient difference between Chinese and NA drywall is in the number and amount of volatile sulfur compounds emitted.

The data and analysis presented here are preliminary results from an ongoing study of drywall emissions. It was not possible to do an exposure and risk assessment on discreet chemical compounds. As specific chemical characterization data become available from the chamber testing, a more comprehensive assessment will be carried out.

I. Background

CPSC has received nearly 1900 consumer complaints reporting corrosion/accelerated aging of metal components in both new and recently renovated homes. A spectrum of health effects have been reported by residents including recurrent headaches, irritated and itchy eyes and skin, difficulty in breathing, persistent cough, runny noses, sinus infections and congestion, sore throats, frequent nosebleeds, and asthma attacks. Frequently, complaints note that affected homes have an offensive or unpleasant odor. Drywall imported from China has been implicated as the probable underlying cause of reported problems, but it should be noted that other home materials and furnishings have not been ruled out as primary or contributing causes.

In an effort to address increasing consumer concerns about imported drywall, CPSC staff has undertaken a multi-track test program to evaluate the possible relationship between drywall and the health symptoms reported by affected homeowners. The specific elements of this test program include laboratory elemental characterization, chamber studies of domestic and imported drywall emissions, and in-home air sampling.

This report is a preliminary evaluation of data from the drywall chamber testing. CPSC staff contracted with Lawrence Berkley National Laboratory (LBL) to conduct chamber testing of drywall samples. The purpose of the laboratory chamber tests is to separate and isolate the drywall's chemical emissions from those of other products that can be found in the home (*e.g.*, wood products, carpets, cleaners, paint, adhesives, and beauty products) so that a determination may be made as to what gases are emitted from each drywall sample. It is important to be able to understand whether reported health-related symptoms might be related to the drywall, to other environmental factors or contaminants in the home, and/or other home materials and furnishings, or to combinations or interactions between any of these factors.

II. Methodology

The objective of the LBL small chamber emission testing is to measure chemical-specific emissions from drywall in a controlled, laboratory system in order to develop quantitative data that will enable CPSC technical staff to model the exposure and perform a health evaluation. The measured emission factors are presented in a way that is sufficient for estimating exposure concentrations related to the amount of a drywall in the dwelling.

A. Drywall Samples

CPSC staff provided thirty samples of drywall to LBL for testing—17 from Chinese sources and 13 from other sources[1]. The drywall samples were collected by CPSC staff directly from warehouses, suppliers, and manufacturers. The samples were not obtained from individual homes, and were not painted, coated, or otherwise modified.

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[1] In this report, non-Chinese drywall is referred to as North American or NA.

B. Chamber methods

This preliminary evaluation is based on 17 samples (5 Chinese, 12 North American). The chamber testing is being conducted in two phases. This report is solely on preliminary Phase I results.

The Phase I studies (see Appendix A for details) are comprised of chamber setup (including construction of 6-liter stainless steel pre-conditioning chambers and design of internal components of the 10.5-liter stainless steel emission chamber to allow for free suspension of the drywall samples), and quick throughput running of the supplied drywall samples. The Phase I studies were designed to:

- screen drywall samples in controlled chambers to identify the chemicals (primarily reactive sulfur gases and volatile sulfur chemicals [VSCs] but also the major volatile organic compounds [VOCs] and other irritant gases) that may be emitted from drywall; and
- quantify emission factors relative to the surface area of the material for the chemicals identified in the emission stream.

The results of the studies will be used to calculate and report steady-state indoor concentrations for the identified chemicals based on typical home ventilation and the amount of drywall in a home.

LBL measured emissions from 6-inch square samples of drywall prepared from samples provided by CPSC. Emissions were measured in 10.5 L chambers with a ventilation rate of 0.5 to 1.0 L/minute. Drywall samples were exposed on both sides. Emission testing was performed at relatively high humidity (up to 80% relative humidity) and temperature (about 100 ºF). These conditions enhance emissions and improve sensitivity in the preliminary stages of the study.

Emission rates are presented as micrograms emitted per total sample area per hour ($\mu g/m^2/h$). LBL reported emission rates of total volatile organic compounds (TVOCs) (as toluene equivalents[2]), total volatile sulfur compounds (TVSCs) (as sulfur equivalents[3]), formaldehyde, and acetaldehyde. TVSCs include organic sulfur compounds. Data on TVOCs and TVSCs were available on the five Chinese samples and five of the 12 North American samples. Emissions were measured chromatographically by parallel mass spectrometry and dual plasma sulfur chemiluminescence; carbonyls were analyzed by high performance liquid chromatography. Future work will include low molecular weight sulfur compounds such as sulfur dioxide, hydrogen sulfide, and carbonyl sulfide.

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[2] VOCs were quantified as toluene equivalent mass; *i.e.*, a single calibration curve was prepared using toluene to relate the mass spectrometer response (peak area) for a given chemical in the chromatogram to the mass of the chemical injected in the analysis.

[3] VSCs were quantified using the response from the sulfur chemiluminescence detector. The detector responds only to the mass of sulfur, not the mass of individual chemicals. Therefore, the calibration response factor is prepared using an arbitrary sulfur containing chemical, and the single response factor is generally relevant to all other sulfur containing chemicals. The calibration response factor is reported as mass of sulfur per instrument response (peak area).

C. Indoor Air Modeling

Indoor concentrations of pollutants were estimated with a single-zone mass-balance model:

$$C = (E/a)*(S/V) \tag{1}$$

> where: C, concentration, μg/m^3; E, emission rate, μg/m^2/h; a, air exchange rate, air changes per hour, or h^{-1}; S/V, surface-to-volume ratio, m^2/m^3.

Emission rates were measured in a small chamber by LBL. The air exchange rate[4], or air changes per hour (ACH), is a key determinant of indoor air concentrations of pollutants. Preliminary information shows that the average air exchange rate for affected homes is about 0.15 h^{-1}; that is, 15% of the indoor air is effectively replaced every hour by natural ventilation. This low air exchange rate is consistent with new construction and the use of air conditioning, given that most of the reportedly affected homes are in a warm, humid climate (Koontz and Rector, 1993; Murray and Burmaster, 1995). S/V is the ratio of the drywall surface area to the house volume. S/V was estimated from a national survey of the U.S. housing stock (Persily *et al.,* 2006). S/V was calculated from floor plans for selected small (DH-A(2)), medium (DH-B(2)), and large (DH-C(1)) homes (Table 1). Drywall was assumed to cover all internal walls and ceilings. Openings for doors and windows were ignored. S/V was approximately 1.6 m^2/m^3 for the small home and 1.2 m^2/m^3 for medium and large homes. Based on preliminary information, the average floor area of the affected homes is about 3,000 ft^2. Therefore, S/V was assumed to be 1.2 m^2/m^3, based on DH-C(1).

Table 1. Surface-to-Volume Ratios of Selected Homes

Home [a]	Floor Area (ft^2)	Floor Area (m^2)	Volume (m^3)	Drywall Area [b] (m^2)	S/V (m^2/m^3)
DH-A(2)	1152	107	261	410	1.6
DH-B(2)	1942	180	440	545	1.2
DH-C(1)	2966	276	672	832	1.2

[a] Persily *et al.,* 2006.

[b] Assumes all interior walls and ceilings are covered with drywall.

D. Summaries of Toxicity Information on Chemicals of Interest

CPSC staff developed summaries of readily available toxicity information on the chemical compounds of potential health concern found in this early Phase I testing. The toxicity summaries emphasize intermediate and chronic inhalation toxicity which is most relevant to the likely exposure scenarios for affected residents. Due to significant time constraints, staff did not review primary scientific studies cited by authoritative sources as the basis of specific regulated or recommended guideline exposure levels of concern.

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[4] The air exchange rate is the rate at which outside air replaces indoor air in a given space.

Most information reported in the results section below has been extracted from authoritative sources including the various datasets that comprise the National Library of Medicine's TOXNET dataset, such as the Hazardous Substances Data Bank (HSDB). Attention is focused primarily on regulatory and guideline levels relevant to low to moderate exposure levels over longer time frames.

III. Results

A. Phase I Chamber Data (for 17 Samples)

Emission rates measured by LBL are summarized in Appendix C, Table C-1. Emission rates for individual volatile organic compounds (VOCs), except for formaldehyde and acetaldehyde, are not yet available. However, as many as 60 individual compounds were present. Preliminary identification of major VOCs present in drywall emissions includes alkanes, aldehydes, siloxanes, and phenols. Terpenes, enols, chloroalkanes, perfluoroalkanes, and disulfides were occasionally seen. The volatile sulfur compounds included in the reported TVSC emission rate include organic sulfur compounds; individual volatile sulfur compounds have not yet been identified. The emission rates for acetaldehyde were adjusted by subtracting the values for sample blanks, because the blank values were relatively high in comparison to the experimental levels for this compound. Other emission rates are as reported by LBL; the blanks (not shown) were either low or zero.

In general, the emission rates from Chinese and North American drywall samples for TVOCs, formaldehyde, and acetaldehyde appear to be roughly similar (Figure C-1, panels A-F). The most notable difference is in the emission of TVSCs. Both the number of compounds detected and the emission rates are generally greater in the Chinese samples (Figure C-1, panels C and D). Samples C3 and C4 had the greatest TVSC emission rates. In a separate study of some of the same samples described here (Garland and Greene, 2009), nearly all of the Chinese drywall samples tested had elevated levels of elemental sulfur, as compared to North American samples. Samples C1, C3, and C4 had the highest levels of elemental sulfur.[5] However, the preliminary nature of the data and the limited sample size preclude statistical analysis or drawing of firm conclusions at this time.

Drywall samples of total area 0.046 m^2 (6-inch square; both sides exposed) were tested in a 10.5 L chamber with typical ventilation rates of 0.5 L/min (0.03 m^3/h) to 1.0 L/min (0.06 m^3/h). Dividing the sample area by the ventilation rate gives an effective loading rate of 1.5 m^2h/m^3. For comparison, dividing the surface-to-volume ratio of a typical home (1.2 m^2/m^3) by a typical air exchange rate of 0.5 h^{-1} gives an effective loading rate of 2.4 m^2h/m^3. Thus, the effective loading rate in the chamber is slightly lower than that in a typical residence. This gives us confidence that the concentrations in the chamber are not sufficient to suppress the emission rate relative to a residence and, therefore, that the chamber data are suitable for exposure modeling.

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[5] The present report and the report from Garland and Greene (2009), used different sample numbering schemes. See Appendix B for a conversion key.

B. Estimated Indoor Air Concentrations

Estimated indoor air concentrations of pollutants are summarized in Appendix C, Table C-1. The utility of these results is limited, because individual TVOCs and TVSCs have not been quantified. The maximum formaldehyde concentration of 127 $\mu g/m^3$ is equivalent to about 100 ppb.[6]

Indoor concentrations were estimated with a simple one-zone mass-balance model. A single-zone model is justified in this case, in part, because the homes of interest generally have central air conditioning, which leads to rapid mixing of the air between rooms. In the absence of rapid mixing, pollutant levels are expected to be slightly greater in smaller rooms. A single-zone model is also justified because drywall is typically present in every room. Steady-state conditions were assumed, because drywall is an integral part of the residence.

Reversible sinks and reactive decay were not considered in this preliminary modeling exercise. In reality, furnishings and surfaces in a home may reversibly adsorb VOCs and other compounds and then release them as the indoor air concentration declines with time. In fact, drywall is a significant sink for many compounds. Some compounds, such as aldehydes and sulfur oxides, may react irreversibly with other compounds in air or with surfaces in the home. Reversible sinks and reactive decay processes tend to reduce indoor levels of pollutants.

While the emission testing was performed under conditions of high humidity and temperature to enhance emissions and improve sensitivity, preliminary results suggest that affected homes may have relatively high humidity (approximately 80% relative humidity) and high temperatures (approximately 80 ºF) indoors. Thus, the testing conditions may be considered as a reflection of the actual situation of some homes.

As discussed above, the air exchange rate (ACH) is an important determinant of indoor air concentrations of pollutants. A lower ACH leads to higher concentrations for indoor sources, and may be associated with indoor air quality problems. Figure C-2 (Appendix C) shows the effect of varying the ACH on the estimated indoor levels of formaldehyde and TVSCs. Average ACH in U.S. homes is about 0.35 to 0.5 h^{-1}, depending on the season (Koontz and Rector, 1993; Murray and Burmaster, 1995). In this case, preliminary investigation of affected homes indicates somewhat lower ACH (approximately 0.15 h^{-1}).

C. Chemicals

This section provides summaries of readily available toxicity information on the chemical compounds of potential health concern found in the limited Phase I testing of 17 of 30 drywall samples. The staff cautions that inclusion of a substance in this discussion does not necessarily imply that adverse health effects are expected to be associated with drywall products, because exposure and risk depend on a number of factors, including the amount of a substance to which a person might be exposed, which cannot be determined for most chemicals at this time. The toxicity summaries emphasize

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[6] For formaldehyde, 1 $\mu g/m^3$ is equivalent to about 0.806 ppb.

intermediate and chronic inhalation toxicity which is most relevant to the likely exposure scenarios for drywall.[7]

Most information reported below has been extracted from authoritative sources including the various datasets that comprise the National Library of Medicine's TOXNET dataset, such as the Hazardous Substances Data Bank (HSDB), as well as the U.S. Environmental Protection Agency's Integrated Risk Information System (IRIS) reviews and assessments. Attention is focused primarily on regulatory and guideline levels relevant to low to moderate exposure levels over longer time frames. These guidelines included EPA's Reference Concentrations (RfCs), the Agency for Toxic Substances and Disease Registry (ATSDR) Minimum Risk Levels (MRLs), the American Industrial Hygiene Association's (AIHA) Emergency Response Preparedness Guidelines (ERPGs), and California's Office of Environmental Health Hazard Assessment (OEHHA) Reference Exposure Limits (RELs).

A reference exposure level (REL) is an airborne level of a chemical that is not anticipated to present a significant risk of an adverse non-cancer health effect. EPA RfCs are estimates of a continuous inhalation exposure of the human population, including populations with pre-existing conditions or sensitivities, which is likely to be without appreciable risk of deleterious non-cancer effects during a lifetime (EPA 1994). An ATSDR MRL is an estimate of the daily human exposure to a hazardous substance that is likely to be without appreciable risk of adverse non-cancer health effects over a specified duration of exposure (http://www.atsdr.cdc.gov/mrls). MRLs are set below levels that, based on current information, might cause adverse health effects in the people most sensitive to such substance-induced effects. MRLs are derived for acute (1-14 days), intermediate (>14-364 days), and chronic (365 days and longer) exposure durations. Because of built-in uncertainty factors, exposure to a concentration above an RfC or MRL is not necessarily expected to cause symptoms or illness. RfCs and MRLs are not intended to define clean up or action levels, or to delineate a level that is likely to cause adverse health effects.

Health-based guidelines for community exposures are not available for many chemicals; therefore, the CPSC staff also looked at existing occupational exposure guidelines from the National Institute for Occupational Safety and Health (NIOSH), the American Conference of Governmental Industrial Hygienists (ACGIH), the Occupational Safety and Health Administration, and AIHA. However, occupational levels are not usually appropriate for application to community settings for a variety of reasons. For example, the population in residential settings is more diverse (*e.g.*, children, elderly) and may have greater susceptibility as a result of pre-existing health conditions. Furthermore, exposure times in homes can vary substantially from those in occupational settings (*e.g.*, longer than an 8 hour workday), as can the circumstances of exposure.

1. Sulfur and Sulfur-Containing Chemicals

Individual chemicals in the TVSCs have not yet been identified by LBL, therefore, the selection of sulfur-containing chemicals included in this preliminary toxicity report was

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[7] It should be clearly understood that there are difficulties with detection methods for some of the sulfur containing chemicals addressed below. Readers are cautioned that these individual chemicals have not necessarily been identified at levels of concern, if at all, in LBL's drywall emission studies.

based on staff's expert judgment and is focused on some key chemicals of potential concern; it should not be considered a final list. Various factors were considered during the selection process including known chemical constituents of drywall, characteristics of health symptoms, odors and accelerated metal aging reported in consumer complaints, available scientific reports from federal and state authorities and independent contractors concerning Chinese and domestic drywall components and emissions, and environmental conditions in homes that might influence the chemistry/stability of sulfur-based drywall constituents.

Elemental Sulfur (S)

Elemental sulfur is a ubiquitous component of the natural environment where it exists as a relatively soft yellow crystalline mineral that, unlike its reduced gas products, is virtually odorless. It is used industrially in many ways, particularly during vulcanization of rubber and as the raw material needed for production of many sulfur chemicals. It has also long been used as a pesticide and fungicide and is currently registered by EPA for this use, and is used as a fertilizer.

According to available information from EPA (EPA, 1991), sulfur has low toxicity and poses very little if any risk to human health. Chronic low level exposure to elemental sulfur is generally considered safe. It is not a skin sensitizer but apparently can cause some ocular, dermal and inhalation irritation. Occupational studies of miners with lifetime exposures to sulfur dust (and sulfur dioxide gas) report adverse health effects, including ocular and respiratory disturbance and chronic bronchitis and sinus problems. Field workers spreading sulfur dust containing products have also reported eye and skin irritation, therefore, EPA requires outdoor sulfur products to have labeling advising users of a 24-hour reentry interval and the need for protective clothing.

Exposure to elemental sulfur is not known to be associated with carcinogenic, teratogenic, or reproductive risk. Neither EPA, ATSDR nor OEHHA have made any recommendations regarding health-based inhalation guidelines for elemental sulfur (RfC, MRLs, RELs) (nor regarding oral toxicity and carcinogenicity potential guidelines).

Sulfur Compounds

Several sulfur containing compounds are characterized by pungent offensive odors that are described as smelling like rotten eggs, burnt matches, fireworks, etc. The odors are typically noticed at low levels that are generally sub-threshold for initiation of health effects. The following section addresses the known information on toxicity of various malodorous sulfur compounds of possible relevance to drywall complaints.

Hydrogen Sulfide (H_2S)

Hydrogen sulfide is a colorless gas that has a characteristic rotten egg odor. It is environmentally ubiquitous being produced naturally in gases emitted by volcanoes, sulfur springs, and natural gas and oil fields, biochemically by sulfur-reducing bacterial activity (including bacteria found in human intestines and oral cavity), and by various industrial processes including oil refining, paper production, sewage treatment, iron smelting and viscose rayon production.

Reported ambient air concentrations of H_2S are about 0.11 – 0.33 parts per billion (ppb) from natural sources, almost 1 ppb in urban areas and much higher levels (>90 ppb) in areas near natural or known industrial sources. A study of residential H_2S concentrations in five homes, in Dakota City/South Sioux City, Nebraska, reports that peak levels in one home routinely exceeded 90 ppb, (from 20 minutes to 3 hours on 10 of 30 monitoring days) which is not considered typical. The maximum levels measured exceeded the upper detection limit of the measuring device (ATSDR, 1997).

The odor threshold for H_2S in air is reported to be approximately 1-13 ppb. At high levels, the ability to detect the noxious odor can become compromised, meaning exposed individuals can lose their ability to recognize harmful environments.

The primary route of exposure to H_2S is via inhalation and diffusion occurs readily across the lung bed into the bloodstream. It is then rapidly oxidized to sulfate (primarily) by the liver and excreted in urine. At extremely high concentrations, death is possible (>500 ppm). At much lower exposures, H_2S can be an ocular and respiratory irritant (nose, throat, and lungs) and can also affect the nervous system.

The ATSDR acute inhalation MRL for H_2S is 70 ppb for exposures up to 14 days. This MRL is based on a human study where 2/10 subjects experienced >30% alteration in airway resistance and conductance, indicative of bronchial obstruction, consequent to a 30 minute exposure to 2000 ppb; also, 3/10 subjects reported headaches (Jappinen et al., 1990). This MRL has an uncertainty factor of 27 (3 for use of lowest observed adverse effect level (LOAEL); 3 for human variability; 3 for database deficiencies).

The ATSDR intermediate inhalation MRL for H_2S is 20 ppb, for exposures ranging from 15 to 356 days. This MRL is based on an animal study in which male Sprague-Dawley rats were exposed to 0, 10, 30, or 80 ppm H_2S for 6 hours/day, 7 days/week for a total of 10 week (12 rats per group). It is based on the 10 ppm no observed adverse effect level (NOAEL) and the 30 ppm LOAEL for loss of olfactory neurons and basal cell hyperplasia in nasal lining (Brenneman, James et al., 2000). This MRL has an uncertainty factor of 30 (3 for animal to human extrapolation; 10 to account for human variability).

The current IRIS RfC of 0.002 mg/m^3 (1.4 ppb) is also based on the olfactory nasal mucosa lesions reported by Brenneman *et al.* (2000). The point of departure, adjusted for the human equivalent concentration($NOAEL_{(HEC)}$), was 0.64 mg/m^3 and was divided by an uncertainty factor of 300 (3 for interspecies extrapolation; 10 for sensitive populations; 10 for subchronic exposure). There is medium to high confidence in this RfC.

California OEHHA's non-cancer chronic inhalation CREL for H_2S is 10 $\mu g/m^3$.

Carbon Disulfide (CS_2)

Carbon disulfide is a volatile clear colorless or faintly yellow liquid that can evaporate at room temperature (boiling point 46.5°F at 760 torr). Pure CS_2 has an almost sweet chloroform-like smell, but impure CS_2 has an unpleasant rotting cabbage/radish odor. Small amounts are generated naturally in volcanic and marshy environments but most CS_2 is produced by industry. Primary use is also in industrial settings for manufacture of rayon, cellophane and carbon tetrachloride; demand for these products has dropped. It is also used in production of pesticides and rubber.

Several odor thresholds for CS_2 in air have been reported between the low and high thresholds of 8 ppb and 7390 ppb, reported by Ruth (1986). Subject odor detection response rates of 50% at 100 ppb and 100% at 200 ppb are reported by MCA (1968).

Exposure to CS_2 is most likely to occur from industrial release to the air; some contamination of drinking water has also been reported (ATSDR, 1996). Minimal inhalation exposure is normally expected in home settings.

The ATSDR chronic inhalation MRL of 0.3 ppm assuming human exposure for 8 hours/day, 5 days/week is based on an occupational study of male workers in a rayon manufacturing plant who exhibited a LOAEL of 7.6 ppm determined for reductions in certain maximum conduction velocities of motor (ulnar and peroneal) and sensory nerves (sural) (Johnson *et al.,* 1983). This MRL has an uncertainty factor of 30 (3 for use of LOAEL; 10 for human variability).

The current EPA IRIS CS_2 inhalation reference concentration (RfC) of 0.7 mg/m^3 (225 ppb) is based on a benchmark concentration (human-equivalent) of 19.7 mg/m^3 (6.3 ppm) divided by an uncertainty factor of 30 (Johnson *et al.,* 1983).

EPA also has derived an oral reference dose (RfD) of 0.1 mg/kg/day based on a NOAEL of 11 mg/kg/day carbon disulfide for fetal toxicity in rabbits following inhalation exposure (Hardin *et al.,* 1981).

California OEHHA’s non-cancer chronic inhalation CREL for CS_2 is 800 µg/m^3.

Carbonyl Sulfide (COS)

Carbonyl sulfide is an odorous sulfur gas that is produced naturally by volcanoes, salt marshes and, according to an ATSDR Exposure Investigation (EI) report (2007), is the most abundant atmospheric sulfur compound, averaging 1 ppb. It is also produced industrially in paper and pulp mills, and in rayon manufacturing and is known to be a breakdown product of carbon disulfide (CS_2).

Despite being listed by EPA as a “Hazardous Air Pollutant” (HAP) and reported as having narcotic effects at high levels and irritant ocular and dermal effects at lower levels, surprisingly little information on COS levels of health concern was located in TOXNET databases. In particular, neither EPA, ATSDR nor OEHHA have made any recommendations regarding health-based inhalation guidelines (RfC, MRLs, RELs) (nor oral toxicity and carcinogenicity potential guidelines).

The aforementioned ATSDR EI report (2007) notes that COS is an odorous respiratory irritant that is immediately metabolized to H_2S in humans. Although low-level COS exposure studies are unavailable, it is expected to have qualitatively similar health effects on the respiratory system as H_2S, but it is also expected to be somewhat less potent because it is comparatively less soluble, less acidic, and thus expected to be less reactive than H_2S, with a higher odor detection threshold.

Sulfur Dioxide (SO_2)

Sulfur dioxide is a non-flammable, odorous gas that is ubiquitous in the environment. It is generated primarily by industrial activities involving combustion of fossil fuels in power plants and smelting plants. A significant amount of SO_2 is also generated by consumer use of fossil fuels to power vehicles, lawnmowers, generators and other engine-driven tools, and to generate heat for cooking/heating purposes. Such activities can have significant influence on an individual's microenvironment and their personal exposure to SO_2. As with other sulfur compounds, volcanic activity results in natural production of SO_2.

After being released into the air, SO_2 can be dispersed far from its point of origin to negatively impact distant communities. SO_2 can be converted into other sulfur compounds such as sulfur trioxide, sulfuric acid, and sulfates. It can also dissolve readily in water to form sulfurous acid. Acidic sulfur compounds can contribute to formation of acid rain which can then damage trees, plants, open bodies of water, and buildings, monuments, etc. More importantly, as outlined below, it can cause significant adverse health effects in exposed individuals, particularly in the sensitive population of asthmatics, and also in children and the elderly. SO_2 is regarded worldwide as a dangerous air pollutant.

Exposure to SO_2 occurs primarily by inhalation and also by direct contact with skin, eyes and mucous membranes of the respiratory tract. Irritant effects on mucous membranes are seen at SO_2 levels of about 10-20 ppm, and it is known that SO_2 can interact with the moisture in membranes to form sulfurous acid (H_2SO_3), which is a severe irritant and inhibitor of mucociliary transport. In healthy adults, worsening effects of local airway irritation advance progressively from increased airway resistance at 5 ppm, to sneezing and coughing at 10 ppm, and bronchospasm at 20 ppm. It is possible for healthy individuals to tolerate exposures between 50 and 100 ppm for short durations (up to 1 hour) but death can occur with longer exposure durations or with higher levels. Asthmatics are much more sensitive to SO_2, with increased airway resistance seen at just 0.1 ppm with mild exercise. Note: this level is below the range of 1 to 3 ppm at which most people can detect the pungent odor of SO_2. Children may be more vulnerable to corrosive agents due to smaller airway diameters and higher ventilation rates. In rare cases, SO_2 can trigger new onset reactive airways dysfunction syndrome (RADS) in individuals with no history of prior bronchospasm. Chronic exposure can alter olfaction, interfering with the ability to detect low levels of SO_2 and resulting in prolonged avoidable exposure (ATSDR- MMGI).

The ATSDR acute inhalation MRL for SO_2 is 10 ppb for exposures up to 14 days. This MRL is based on a human study of mild asthmatics (Shepherd *et al.*, 1981). After inhaling 100 ppb through a mouthpiece for 10 minutes, 2 subjects exhibited slight bronchoconstriction while performing moderate exercise; at >250 ppb, all 7 subjects exhibited increased airway resistance during moderate exercise. This MRL has an uncertainty factor of 9 (3 for use of a minimal LOAEL; 3 for human variability).

ATSDR considers the available data is insufficient to allow derivation of an intermediate (14-364 days) or long term (>364 day) inhalation MRL.

In the US, SO_2 is one of only six criteria air pollutants for which primary and secondary limits are set by EPA's National Ambient Air Quality Standards (NAAQS). The primary standard limits are intended to protect public health including sensitive populations such as asthmatics, children and the elderly. The secondary standard limits are intended to protect public welfare, including protection against decreased visibility, damage to animals, crops vegetation and buildings. Furthermore, the provisions of the Clean Air Act require EPA to conduct periodic review of the adequacy of NAAQS, and update them as found necessary *(EPA is currently in the process of reviewing the NAAQS for* SO_2*).*

EPA's primary NAAQS for SO_2 are meant to protect against health effects resulting from acute and long term exposure to environmental chemicals. Currently, the primary NAAQS for SO_2 recommend that the long-term, 1-year average concentrations of SO_2 should not exceed 0.03 ppm (chronic exposure) and the short-term, 24-hour average concentration should not exceed 0.14 ppm more than once a year. *(The secondary NAAQS for* SO_2 *is 500 ppb as a 3 h TWA that should not be exceeded more than once a year.)* There is no EPA IRIS RfC for SO_2.

California OEHHA has not identified a non-cancer inhalation CREL for SO_2 but does define an acute inhalation REL for SO_2 as 660 $\mu g/m^3$.

2. Volatile Organic Compounds and Certain Carbonyl Species

Discussed here are certain chemicals identified in the emission testing, including volatile organic compounds (VOCs) and the smaller carbonyl species, formaldehyde and acetaldehyde. In addition to the quantified emission factors for total VOCs, the results of analysis by mass spectroscopy were reported, which identified some of the emitted substances for some of the samples.

For the VOCs analysis, dozens of chemicals were identified or tentatively identified as emitting from the drywall samples under the conditions of the study. The emission results were reported as total VOCs. Although emission factors for individual chemicals were not available for quantitative analysis, the staff inspected the data to identify the chemicals that were found at relatively high levels, those chemicals that were common to at least several of the samples, and those that may be significant toxicologically. See Appendix D for a table of selected volatile organic compounds and carbonyls.

Two types of compounds were detected in most samples: siloxanes, including dodecamethylcyclohexasiloxane and decamethylcyclopentasiloxane, and aldehydes, including formaldehyde and acetaldehyde, as well as benzaldehyde, hexanal, heptanal, octanal, nonanal, and decanal.

Also detected in many, but not all, samples were certain hydrocarbons and halogenated hydrocarbons, including 1-chlorooctane, 1-chlorononane, 1-chlorodecane, 1-chloro-undecane, 1-chlorododecane, 3-methyl-tridecane, tetradecane, hexadecane, and nonadecane.

Other substances detected in only a few samples included fluorinated hydrocarbons, such as perfluoro(methylcyclohexane) and 1,1,1,2,2,3,3,4,4,5,5,6,6-tridecafluoro-hexane; furans, such as tetrahydrofuran, tetrahydro-2,2,4,4-tetramethyl-furan, and

2-pentyl-furan; and other chemicals such as 2,2,4-trimethyl-1,3-pentanediol, acetone, methylene chloride, phenol, and limonene.

Some of these chemicals have been associated with building materials or consumer products. It is not possible to identify the precise source of each of the chemicals associated with the drywall samples. However, many of the substances are known to be used in coatings, inks, and other materials.

Total VOCs

In general, exposures to volatile organic compounds (VOCs) may be associated with perception of odors, and irritation of eyes, nasal membranes, throat, and respiratory tract, although specific substances may cause other adverse health effects, as discussed for some substances referenced below. The effect levels for the many different VOCs may vary by orders of magnitude between the least toxic substances and the most toxic.

Because the potential sources of VOCs in the indoor environment are many, including building materials, furniture, and numerous household products such as paints, paint strippers, other solvents, aerosol sprays, cleaning supplies and disinfectants, air fresheners, glues and adhesives, and many others, measured levels in homes and other places vary widely. Thus, there is not a typical level of VOCs in indoor air. For example, a recent study of 79 homes in Germany found total VOC concentrations ranging from 33 μg/m^3 to 1600 μg/m^3, with a median level of 289 μg/m^3 (Hippelein, 2004).

Similarly, because the specific VOCs making up the total of the VOCs that are present in a particular residence or location also vary widely, there is no particular level of total VOCs that is associated with specific health effects.

In addition, there are no regulatory limits in the U.S. for VOCs as a group. However, because of the concern about VOC levels in indoor air, and because certain building materials are known sources of VOCs, some standards and guidelines provide specifications for maximum indoor air concentrations, or emission rates from products. For example, the State of Washington (Washington State, 1989) established specifications for new state office buildings based on emissions from each product or building material. The limit of 500 μg/m^3 for total VOCs was based on specified chamber testing methods and air concentration modeling.

Likewise, the Carpet and Rug Institute (CRI, 2009) established a program for testing, certification, and labeling of carpet, cushions and adhesives for VOC emissions. Under the terms of the "Green Label" program and the specified test, the limit for total VOC emissions for carpet cushions is 1000 μg/m^2/hr. For carpets and adhesives, the "Green Label Plus" program did not establish a limit for emissions of total VOCs. Instead, this program provides emission limits for specific chemicals, ranging from 8.2 μg/m^2/hr for naphthalene to 410 μg/m^2/hr for styrene.

Aldehydes

Many aldehydes are common industrial chemicals; some are naturally-occurring constituents of fruits and other flora. The main health effects associated with exposure to aldehydes in humans are irritation of eyes, nasal membranes, throat, and respiratory tract.

Formaldehyde

Formaldehyde is a well-studied aldehyde that has wide use in industrial processes and products. Formaldehyde is ubiquitous in the environment from both natural and industrial sources. Outdoor air concentrations tend to range from 5 to 30 parts per billion (ppb), although levels are occasionally measured at several times these values. Concentrations in indoor air also vary widely, and often exceed outdoor levels (HSDB, Formaldehyde).

Health effects of formaldehyde include the irritation and upper respiratory system effects common to other aldehydes. Symptoms are generally noted with exposures at several hundred parts per billion, although some studies indicate measureable effects from long-term exposures to levels below 100 ppb (123 μg/m^3), especially for sensitive individuals (HSDB, Formaldehyde). In general, the reported estimated thresholds are in the range of 625–1250 μg/m^3 (Salonen *et al.*, 2009; Lang *et al.*, 2008).

The indoor guideline values for formaldehyde, recommended with the intention of preventing acute sensory irritation, vary. In order to prevent significant sensory irritation in the general population, the WHO has recommended a guideline value of 100 μg/m^3 as a 30-minute average (WHO, 2001). The Agency for Toxic Substances and Disease Registry has established the minimal risk level (MRL) for chronic exposure to formaldehyde at 8 μg/m^3, based on symptoms of mild irritation of the eyes and upper respiratory tract, and mild damage to the nasal epithelium observed in workers. This MRL includes an uncertainty factor of 30 (3 for the use of the LOAEL, and 10 to account for human variability). The California OEHHA's chronic REL for formaldehyde is 9 μg/m^3. The broad range of these guideline values results from including various safety factors and whether the health guideline value is addressing shorter or longer exposure (*e.g.*, acute, intermediate or life-time).

Formaldehyde is the subject of a U.S. Environmental Protection Agency (EPA) Integrated Risk Information System (IRIS) review and assessment. As indicated in the IRIS record, formaldehyde is a probable human carcinogen. EPA has calculated the inhalation unit risk for formaldehyde. Based on the endpoint of squamous cell carcinoma in laboratory animals, the unit risk is 1.3x10^{-5} per μg/m^3.

Similar to the VOCs, concern about formaldehyde levels in indoor air has resulted in standards and guidelines for formaldehyde air concentrations or emission rates from products. The State of Washington (Washington State, 1989) established specifications for new state office buildings based on emissions from each product or building material. The limit of 50 ppb (61.5 μg/m^3) for formaldehyde was based on specified chamber testing methods and air concentration modeling.

Again, as with VOCs, the Carpet and Rug Institute's voluntary certification also includes formaldehyde emissions. Under the terms of the "Green Label" program and the specified test, the limit for formaldehyde emissions for carpet cushions is 50 μg/m^2/hr, while under the "Green Label Plus" program, the limit for carpets and adhesives is 30 μg/m^2/hr.

Acetaldehyde

Acetaldehyde is environmentally ubiquitous, generally found at low ppb levels in both indoor and outdoor air, although measured concentrations vary widely. Health effects include the irritation and upper respiratory system effects common to other aldehydes (HSDB, Acetaldehyde).

As indicated in the IRIS record, EPA has produced a reference concentration (RfC) for acetaldehyde. Based on the endpoint of degeneration of the olfactory epithelium in laboratory animals, the RfC is 9×10^{-3} mg/m^3. The RfC includes an uncertainty factor of 1000 (a factor of 10 to account for sensitive human populations; a factor of 10 for the interspecies extrapolation and database inadequacies; and a factor of 10 for subchronic to chronic extrapolation). As indicated in the IRIS record, acetaldehyde is a probable human carcinogen. EPA has calculated the inhalation unit risk for acetaldehyde. Based on the endpoint of laryngeal tumors in laboratory animals, the unit risk is 2.2×10^{-6} per µg/m^3. The chronic reference exposure level (CREL) for acetaldehyde is 140 µg/m^3.

Benzaldehyde

Benzaldehyde appears to be commonly measured in the environment, generally at low or sub-ppb levels in both indoor and outdoor air, although measured concentrations have varied by orders of magnitude (HSDB, Benzaldehyde).

In addition to causing sensory irritation, benzaldehyde exposure in humans is associated with central nervous system (CNS) depression at higher exposure levels. CNS impairment and other effects were also reported in laboratory animals exposed to relatively high levels (500-1000 parts per million) for 6 hours per day for 14 days (HSDB, Benzaldehyde).

The American Industrial Hygiene Association’s Workplace Environmental Exposure Level (WEEL) for benzaldehyde is 2000 ppb TWA.

Hexanal

Hexanal appears to be environmentally ubiquitous, generally found at low ppb levels in both indoor and outdoor air, although measured concentrations have varied by orders of magnitude (HSDB, Hexaldehyde).

Few studies have directly assessed the toxicity of hexanal in humans. Authors of a recent study, in which health volunteers were exposed to 0, 2, and 10 parts per million (ppm) n-hexanal for 2 hours, concluded that two hours of exposure to n-hexanal results in mild irritation at 10 ppm, but no adverse effects were noted for exposure at 2 ppm (Ernstgård *et al.,* 2006).

Heptanal, Octanal, Nonanal, Decanal

Like hexanal and other aldehydes, heptanal, octanal, nonanal, and decanal appear to be environmentally ubiquitous, generally found at somewhat lower concentrations than hexanal; *i.e.*, sub-ppb levels in both indoor and outdoor air, with a wide range of measured levels (HSDB, n-Heptanal, Octylaldehyde, Decaldehyde).

Siloxanes

The siloxanes have a number of uses in consumer products and other industrial processes. They have been measured in both outdoor and indoor air at levels generally below 1 ppb.

CPSC staff located no reports of health effects in humans.

Burns-Naas *et al.* (1998a) evaluated the toxicology of decamethylcyclopentasiloxane in laboratory animals exposed, whole body, 6 hours per day, 7 days per week, for 28 days at air concentrations up to 160 ppm. Under these experimental conditions, the authors concluded that exposure to decamethylcyclopentasiloxane by inhalation did not effect humoral immunity, but caused minor changes in hematological, serum chemistry, and organ weight values. These changes appeared transient, as the effects were not evident in animals examined 14 days after exposure ceased. Histopathological changes were noted in the respiratory tract and also appeared to be reversible after exposure ended. The authors concluded that the no observed effect level for systemic toxicity, based on the liver weight changes, was 75 ppm. However, the authors noted an increase in the incidence of goblet cell proliferation of the nasal cavity and the incidence and severity of submucosal inflammation at 75 ppm. Further, the submucosal inflammation appeared to be reversible following cessation of exposure, while the goblet cell proliferation was still evident 14 days after cessation of exposure. No effects were noted at 25 ppm.

Burns-Naas *et al.* (1998b) also evaluated decamethylcyclopentasiloxane in laboratory animals exposed, nose-only, 6 hours per day, 5 days per week for 3 months at air concentrations up to 224 ppm. Dose-related liver effects were noted, as well as respiratory system effects including an increase in focal macrophage accumulation and interstitial inflammation in the lungs of animals exposed at 224 ppm. Given the lack of histopathological effects in the liver, the authors concluded that the liver is not a target organ.

The manufacturer of decamethylcyclopentasiloxane recommends an exposure guideline of 10 ppm TWA (time-weighted average).

Hydrocarbons

Little information was located for the reported aliphatic hydrocarbons, particularly the chloroalkanes.

One of the reported substances, tetradecane, appears to be nearly ubiquitous in the environment, generally found at low parts per billion levels in both indoor and outdoor air, although measured concentrations have varied by orders of magnitude (HSDB, n-Tetradecane).

In general, acute inhalation exposure to aliphatic hydrocarbons, such as tetradecane and other related substances, may be associated with cardiac arrhythmias and CNS depression, depending on the level of exposure. Smaller hydrocarbons can cause asphyxiation in conditions of poor ventilation. Intentional high exposures such as associated with sniffing abuse can result in sudden death, encephalopathy, neurological impairment, kidney and liver toxicity, and other effects. Longer term exposures to certain hydrocarbons, particularly in intentional abuse, can result in hematologic effects, liver and kidney effects, and neurological and neuropsychiatric effects (HSDB, n-Tetradecane).

Other hydrocarbons, while not specifically identified in the drywall sampling, are better characterized for human health effects and for dose-response. For example, n-hexane is well-studied, and one reference indicates that n-hexane may be the most toxic alkane (Cavender, 1994). The main effects of inhalation exposure to n-hexane in humans are peripheral neuropathy and other neurological effects. As indicated in the IRIS record, EPA has produced a reference concentration for n-hexane. Based on the endpoint of peripheral neuropathy in laboratory animals, the RfC is 0.7 mg/m^3. The RfC includes an uncertainty factor of 300 (10 for sensitive human populations; 3 for interspecies extrapolation, 3 for database inadequacies, and 3 to extrapolate to chronic exposure from data in a less-than lifetime study).

The chronic MRL for n-hexane is 0.6 ppm (2.1 mg/m^3), based on neurological effects in workers. The MRL includes an uncertainty factor of 100 (10 for the use of the LOAEL, and 10 to account for human variability). The chronic reference exposure level (CREL) is 7000 µg/m^3 (7 mg/m^3).

Limited toxicity information was located for the chlorinated species; 1-chlorooctane inhalation exposure is associated with central nervous effects such as dizziness, weakness, and peripheral pain or numbness (HSDB, 1 Chlorooctane).

Other Chemicals

Tetrahydrofuran

Tetrahydrofuran is an industrial solvent and intermediate. Vapor is irritating to the skin, eyes, and upper respiratory system. It has been detected in both outdoor and indoor air.

2,2,4-Trimethyl-1,3-pentanediol

This substance is an industrial intermediate and solvent used in production of resins, inks, and other materials. Little data was located for this chemical. It may be an irritant and it has been measured in air at low part per billion levels (HSDB, 2,2,4-Trimethyl-1,3-pentanediol).

Acetone

Acetone is a common industrial chemical that is also a metabolic product in plants and animals. It is found in both indoor and outdoor air generally at low ppb concentrations. It has a relatively low order of toxicity, with irritation being the primary effect at lower concentrations. Exposure to high levels (*i.e.*, several thousand ppm) can lead to serious CNS and respiratory effects (HSDB, Acetone). The chronic MRL for acetone is 13 ppm (31 mg/m^3), based on neurological effects in humans. The MRL includes an uncertainty factor of 100 (10 for the use of the LOAEL, and 10 to account for human variability).

Methylene chloride

Methylene chloride is typically encountered from use of certain paint removers, degreasers, and solvents. Air concentrations of methylene chloride are generally at sub-ppb levels outdoors; indoor air concentrations may be somewhat higher, *i.e.*, low ppb. Because exposures under conditions of use can be high, available information about health effects largely concerns exposures of several hundred ppm (HSDB, Dichloromethane). One study of a group of workers exposed at air concentrations of 75-100 ppm indicated no long-term effects that could be attributable to methylene chloride (Cherry *et al.,* 1981).

The chronic MRL for methylene chloride is 0.3 ppm (1 mg/m^3), based on liver effects in laboratory animals. The MRL includes an uncertainty factor of 30 (3 for extrapolation from animals to humans, and 10 to account for human variability). As indicated in the EPA IRIS record, methylene chloride is a probable human carcinogen. EPA has calculated the inhalation unit risk for methylene chloride. Based on the endpoint of combined adenomas and carcinomas in laboratory animals, the unit risk is $4.7x10^{-7}$ per $µg/m^3$.

Phenol

Given the relatively low volatility of phenol, exposures have generally been direct contact with the skin or ingestion. However, exposure to vapors has been documented. Phenol is primarily an irritant, but high exposures, including intentional ingestion are associated with severe health effects. Staff found little information concerning inhalation exposures and air levels. One study in a workplace indicated no discernible health effects in workers exposed up to 12.5 mg/m^3 (HSDB, Phenol). The chronic reference exposure (CREL) for phenol is 200 $µg/m^3$.

Limonene

Limonene, and its isomers, is a naturally occurring substance found in fruits, trees, and other plants. It is used in a variety of products, including foods as a flavoring, and in other common products. Limonene is generally found in both outdoor and indoor air at concentrations up to about 80 $µg/m^3$. Limonene is a skin irritant and is associated with skin sensitization. The Workplace Environmental Exposure Level (WEEL) is 30 ppm TWA (170 mg/m^3).

IV. Discussion

The purpose of this preliminary evaluation was to evaluate chemical emissions from NA and Chinese drywall, the possible differences in chemical emissions between the two sources of drywall products, and the possible chemical exposures in homes that contain either of these two sources of drywall.[8]

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[8] There are variety of federal and state regulatory authorities and health guidelines that pertain to chemicals found in homes and in the environment. For the purposes of this evaluation, the CPSC staff utilized an approach which is consistent with CPSC authorities under the Federal Hazardous Substances Act (FHSA). The FHSA defines a *hazardous substance* as any substance or mixture of substances which

The LBL data contained measures for a number of compounds presented in four chemical/chemical subgroups, including: total volatile organic compounds (TVOC), total volatile sulfur compounds (TVSC), formaldehyde, and acetaldehyde. The calculated emission factors for these groups of compounds are listed in Appendix C, Table C-1.

No discernible differences in chemical emissions were noted between drywall products from China and NA drywall, except for total volatile sulfur compounds (TVSCs). Mean emission rates were 12.1 μg/m^2/hr and 0.5 μg/m^2/hr for Chinese and NA drywall respectively. Emissions of total volatile organic compounds (TVOCs)—ranging from about 6.1 μg/m^2/hr to 119.6 μg/m^2/hr—and for formaldehyde—ranging from 4.6 μg/m^2/hr to 15.88 μg/m^2/hr—were not dissimilar from other studies of chemical emissions from drywall (see below). Mean emission rates for TVOCs were 29.5 μg/m^2/hr (Chinese) and 36.6 μg/m^2/hr (NA), and 6.1 μg/m^2/hr (Chinese) and 8.3 μg/m^2/hr (NA) for formaldehyde.

CPSC staff located at least two emission studies of building materials that included gypsum wallboard. One report, by the State of California (Alevantis, 2003), reported formaldehyde emissions of two U.S. drywall samples, under the specific conditions of the study, of 15 and 19 μg/m^2/hr. Another report, by the Environment Institute of the Joint Research Centre of the Commission of the European Communities (Colombo et al., 1990), reported a mean emission rate for two samples of 8.8 μg/m^2/hr.

Both of these reports, while limited in scope and based on methodology that is not identical to the methods used in the current CPSC activity, present data that indicate that the results reported by LBL are consistent with the formaldehyde emission rates for drywall observed in the other studies. The California and European reports also indicated that formaldehyde emissions from drywall was comparable to formaldehyde emissions from other building materials, or in some cases, significantly less than other materials such as particle board.

While both the California and European reports also assessed volatile organic compounds (VOCs), the Colombo *et al.* (1990) study reported results for several individual chemicals, not total VOCs. The California study reported a wide range of total VOC emissions from drywall, from non-detect in a 96-hour test to 61 μg/m^2/hr. Thus, the results reported by LBL are consistent with the total VOC emission rates for drywall observed in at least one other study.

CPSC staff used the reported emission factors in a one-zone mass-balance model to estimate the concentrations of the chemicals in the indoor air of a home that might result from the presence of the drywall. The model accounted for factors, such as air exchange rate and room volume, that impact the concentrations of chemicals in the indoor air. The model did not include sink effects; *i.e.,* the effects of various conditions and contents of a room through which chemicals may be removed from the air due to adsorption onto or absorption into articles in the room, such as furniture and carpeting. The lack of sink effects in the model likely results in estimates that are conservative and

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is toxic, corrosive, an irritant, a strong sensitizer, flammable or combustible, or generates pressure through decomposition, heat or other means, if such substance or mixture of substances may cause substantial personal injury or substantial illness during or as a proximate result of any customary or reasonably foreseeable handling or use, including reasonable foreseeable ingestion by children. Each of the listed hazards has a specific definition in the FHSA (www.cpsc.gov).

higher than what would be encountered in an actual occupied home environment that would typically include sinks.

The mean concentrations in indoor air for the four chemical classes were calculated for North American and Chinese drywall. The largest apparent difference between the two sources of drywall product is seen in the emission factors and estimated residential indoor air concentration for TVSC. The estimated air concentrations of these compounds for the Chinese drywall (mean 96.7 $\mu g/m^3$; standard deviation 135.1 $\mu g/m^3$) were considerably higher than the concentrations of TVSC estimated for the North American drywall (mean 4.3 $\mu g/m^3$; standard deviation 3.3 $\mu g/m^3$). On the other hand, the mean estimated air concentrations of acetaldehyde and formaldehyde (6.7 $\mu g/m^3$ and 66.5 $\mu g/m^3$, respectively) for the NA drywall were somewhat higher than the estimates for Chinese drywall (4.0 $\mu g/m^3$ and 49 $\mu g/m^3$) (Appendix C, Table C-1). Similarly, the concentrations of TVOCs were higher for the North American drywall (mean 292 $\mu g/m^3$) compared to the Chinese samples (mean 236 $\mu g/m^3$).

There are no regulatory limits in the U.S. for total VOCs in indoor air in homes. However, at least one U.S. state specifies that TVOC emissions from each building material used in the construction of state buildings should not result in air concentrations exceeding 500 $\mu g/m^3$ (State of Washington, 1989). For most of the products tested, the model results show that total VOCs in air within a home due to drywall does not exceed this limit.

For formaldehyde, there are a number of health-based inhalation guidelines. For example, the Agency for Toxic Substances and Disease Registry Minimal Risk Level (MRL) for chronic exposure to formaldehyde is 8 $\mu g/m^3$; the State of Washington building materials specification is 50 ppb (61.5 $\mu g/m^3$). The model results for the drywall samples indicate that these inhalation guidelines could be exceeded. However, certain limitations and uncertainties must be recognized. For example, the modeling was done assuming reasonable worst-case conditions, and did not take into account certain factors, such as the reactive nature of formaldehyde, which could affect the air concentration estimates. An evaluation conducted under more complex and perhaps more realistic conditions could provide more refined estimates that might be lower than the estimates presented here. Further, over time, the emission rates for both VOCs and formaldehyde from building materials, such as drywall, might be expected to drop, which would eventually result in lower indoor air concentrations.

The information provided to date for emissions of sulfur-containing compounds are only for the total emissions of certain volatile sulfur compounds. Because of specific testing conditions required for chemicals such as hydrogen sulfide, data on possible emissions of hydrogen sulfide and other compounds are not yet available. The emissions data in the limited sampling conducted so far showed that emission rates for volatile sulfur-containing compounds were considerably higher from Chinese drywall (mean 12.1 $\mu g/m^2/hr$) compared to the emission rates from NA drywall (mean 0.5 $\mu g/m^2/hr$). As presented above, the modeled indoor air concentration estimates using these data were also considerably higher for the Chinese samples than for the NA samples. Because CPSC staff has not located information, such as health-based inhalation screening guidelines, for total volatile sulfur compounds, and because emission data for individual sulfur-containing compounds are not available, the staff is unable to characterize the possible implications of the data at this time.

As indicated above, this preliminary evaluation does not take into account all the expected complexity of an exposure assessment. For example, certain factors that might be expected to significantly influence the evaluation, such as modeling sink effects, were not included. Formaldehyde, especially, is a reactive chemical, and neglecting the effect of sinks and other reactions involving this chemical might be expected to have a significant impact on the model outputs. Furthermore, the work completed to date has not identified or quantified all possible chemicals of interest, and staff has not taken into account other factors, such as possible interactions with other chemicals in a home, that could result in higher or lower estimates of indoor air concentrations. As with any model-based exposure assessment, there are numerous assumptions, limitations, and sources of uncertainty that should be explored further. Thus, this evaluation will be followed by a more comprehensive exposure study once additional data become available.

While the data provided by LBL to date are limited, and the sample size is small, these data provide important information about chemicals that may be emitted from Chinese drywall products that are not also released from NA drywall. Based on these preliminary results, the most salient difference between Chinese and North American drywall is in the number and amount of volatile sulfur compounds emitted. Individual volatile sulfur compounds were not identified. These are likely to consist of organic sulfur compounds and do not include low molecular weight inorganic sulfur compounds such as sulfur oxides and hydrogen sulfide. Emissions of low molecular weight sulfur compounds will be examined in the future.

The data and analysis presented here are preliminary results from an ongoing study of drywall emissions. It was not possible to do an exposure and risk assessment on discreet chemical compounds. As specific chemical characterization data become available from the chamber testing, a more comprehensive assessment will be carried out. Estimates of indoor air concentrations did not adjust for reversible sinks or reactive decay. These factors are expected to reduce indoor air concentrations in actual homes. Thus, the estimates of indoor air concentrations presented here are likely to overestimate actual exposures. In addition, this is one part of a larger effort that includes investigatory studies of drywall composition, affected homes, and corrosion.

APPENDIX A

Sample handling and analysis: This preliminary evaluation is on the first 17 of 30 drywall samples. Briefly, the samples were collected by CPSC staff, individually sealed in low sorption material (Tedlar® bags), shipped to LBL and stored at room temperature until initiation of testing. Six-inch square sections, both sides exposed, were loaded into separate stainless steel pre-conditioning chambers (6 liter) that were set at a specified humidity and ventilated using activated carbon filtered air. The samples were allowed to equilibrate with the elevated humidity prior to testing. Small (10.5 liter) stainless steel chambers housed in a temperature controlled environmental system were used for this preliminary evaluation. All internal surfaces in the emission chambers and sampling lines were either treated for low sorption coating (Sulfinert®) or constructed from low sorption materials (Teflon®).

In order to enhance the magnitude of emissions from drywall in the preliminary evaluation, the samples were tested in the emission chamber at elevated temperature and relative humidity (up to 38°C and 80% relative humidity). The chambers were ventilated with carbon filtered air to prevent the introduction of chemicals from other sources. The ventilation rate was maintained at a flow rate that was at least 20% greater than the air sampling rate with typical flows of 0.5 to 1 liter per minute.

In order to minimize sample loss and maximize sample throughput, the analytical instrumentation was interfaced directly to the emission chambers. The integrated air samples were cryogenically collected on sorbent materials then thermodesorbed and chromatographically separated prior to the simultaneous analysis on two separate chemical detectors.

- For VOCs and VSCs, 3 liter integrated emission samples, collected at 100 cc/min, were sorbed onto Tenax/carbosieve cartridges, thermodesorbed, and separated by gas chromatography. Parallel mass spectrometry and dual plasma sulfur chemiluminescence detection were performed. Identification of analytes was carried out by comparisons between mass spectra (NIST08 database), retention time and/or pure standards.
- For low molecular weight carbonyls, a 60 liter integrated sample was collected at 1 liter/min directly onto dinitrophenylhydrazine (DNPH) coated silica gel cartridges and eluted with 2 ml acetonitrile. Analytes were analyzed by high performance liquid chromatography (HPLC) and quantified using pure standards.
- For reactive sulfur gases, 1 to 3 liter integrated samples were analyzed by cryogenic pre-concentration-thermal desorption. Samples collected at 100 cc/min, were cryogenically pre-concentrated (-50ºC) on Tenax/carbosieve cartridges followed by cold-trapping on glass beads held at -150ºC then thermodesorbed onto the gas chromatograph column (-50ºC initial temp). Analytes were detected with dual plasma sulfur chemoluminesence detection. Initial identification using a pre-mixed calibration gas was carried out to identify mass spectra and retention times.

The results are expressed as material-specific emission rate normalized to the surface area of material (µg/m^2/hr). Since specific characterization of sulfur compounds has not been completed, sulfur gas data is presented as total volatile sulfur compounds (TVSCs).

APPENDIX B

Sample Identification Key

This table compares the sample identification numbers used in the report on chemical analysis of wallboard samples (Garland and Greene, 2009) and the emission data from LBL.

Elemental Analysis	Emission Studies
1	C5
2	
3	C3
4	
5	C4
6	C1
7	C2
8	NA1
9	NA6
10	NA7
11	NA3
12	NA2
13	NA5
14	NA10
15	NA4
16	NA8
17	
	NA9
	NA11
	NA12

Emission Studies	Elemental Analysis
C1	6
C2	7
C3	3
C4	5
C5	1
NA1	8
NA2	12
NA3	11
NA4	15
NA5	13
NA6	9
NA7	10
NA8	16
NA9	
NA10	14
NA11	
NA12	
	17

APPENDIX C

Emission Data

Table C-1. Estimated Indoor Concentrations of Chemicals Emitted by Drywall [a]

Sample ID	TVOC [b, c]			TVSC [d]			Formaldehyde		Acetaldehyde	
	E µg/m²/h	N	Con. µg/m³	E µg/m²/h	N	Con. µg/m³	E µg/m²/h	Con. µg/m³	E [e] µg/m²/h	Con. µg/m³
China										
C1	17.8	50	142	1.41	21	11	4.9	39	0.28	2.3
C2	14.3	28	115	1.82	22	15	6.3	50	0.89	7.1
C3	52.9	68	423	39.79	46	318	6.9	56	0.27	2.2
C4	30.9	67	248	16.82	38	135	7.7	62	0.00	0.0
C5	31.4	58	251	0.59	11	5	4.6	37	1.05	8.4
Mean	29.5	54	236	12.1	28	96.7	6.1	49	0.50	4.0
SD	15.2	16	121	16.9	14	135.1	1.3	11	0.45	3.6
Median	30.9	58	248	1.8	22	15	6.3	50	0.28	2.3
North America [f]										
NA1							8.19	66	1.04	8.3
NA2	19.2	34	154	0.22	4	2	6.83	55	0.00	0.0
NA3				1.24	18	10	8.1	65	1.24	9.9
NA4							7.73	62	0.89	7.1
NA5	6.1	21	49	0.30	3	2	15.88	127	1.33	10.7
NA6							8.15	65	0.96	7.7
NA7							5.8	46	0.25	2.0
NA8							11.41	91	0.88	7.1
NA9	10.5	25	84	0.12	2	1	5.09	41	0.84	6.7
NA10	119.6	60	957	0.63	5	5	7.69	62	0.10	0.8
NA11	27.4	34	219	0.74	5	6	6.79	54	1.70	13.6
NA12							8.13	65	0.71	5.7
Mean	36.6	34.7	292	0.5	6.0	4.3	8.3	66.5	0.8	6.7
SD	47.1	15.2	377	0.4	6.0	3.3	2.8	22.7	0.5	4.1
Median	19.2	33.5	154	0.5	4.0	3.7	7.9	63.3	0.9	7.1

[a] Emission rates measured by Lawrence Berkeley National Laboratory.

[b] TVOC, total volatile organic compounds; TVSC, total volatile sulfur compounds; E, emission rate, µg/m²/h; N, number of compounds detected; Con., estimated concentration in indoor air, µg/m³.

[c] Measured as toluene, *i.e.*, using toluene for the standard response curve.

[d] Measured as sulfur equivalents.

[e] Adjusted by subtracting the mean blank value of 1.8 µg/m²/h.

[f] Includes one Mexican sample. The others are domestic.

APPENDIX C

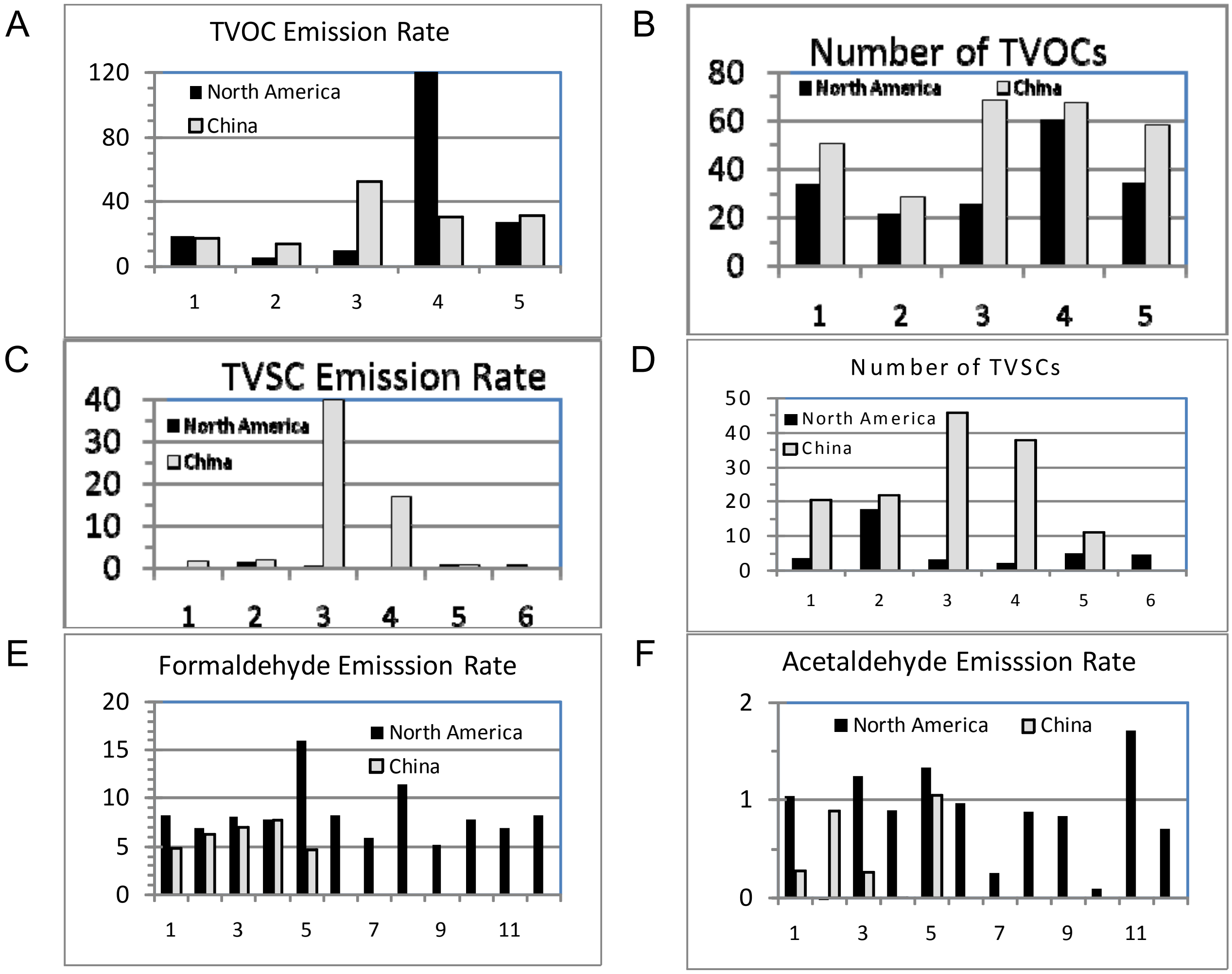

Figure C-1. Chemical emissions from drywall samples. Emission rates (µg/m^2/h) were measured by LBL in a 10.5 L chamber. Number of TVOC's/TVSC's is the number of peaks identified by GC-MS. Solid bars, North America; open bars, China.

APPENDIX C

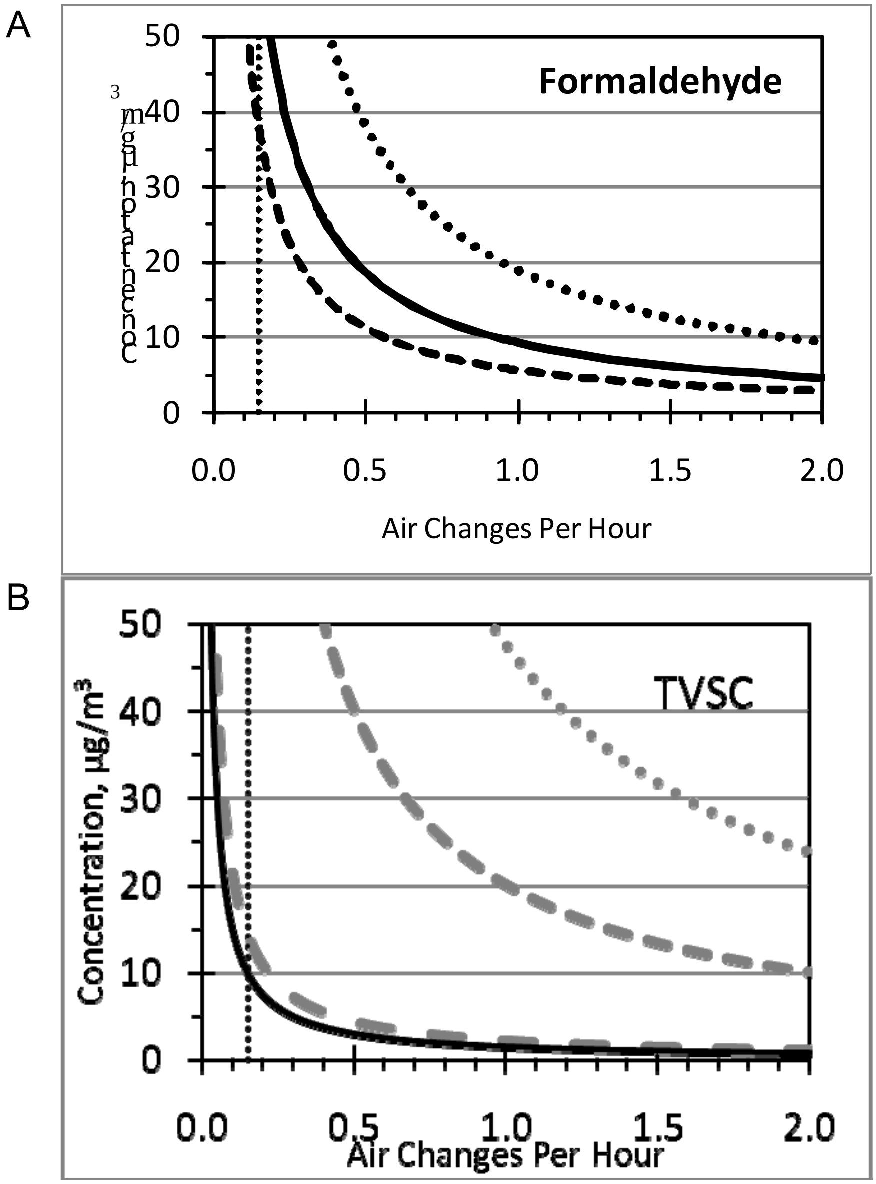

Figure C-2. Dependence of the Modeled Indoor Concentration on Air Exchange Rate.
(A) Formaldehyde. For all tested samples: broken line, lowest emission rate; solid line, median emission rate; dotted line, greatest emission rate. The vertical dotted line indicates 0.15 air changes per hour. (B) Total volatile sulfur compounds: solid black line, sample NA6; broken gray lines, left to right, samples C3, C4, and C5. The vertical dotted line indicates 0.15 air changes per hour.

Appendix D

INFORMATION ON SELECTED VOLATILE ORGANIC COMPOUNDS AND CARBONYLS				
Chemical/CAS#	**Uses/Sources**	**Health Effects**	**Health-based Inhalation Screening Guidelines***	**Odor/threshold**
Formaldehyde/ 50-00-0	Wood products, disinfectant, textiles, paints	Irritation; carcinogen	MRL: Acute: 40 µg/m^3 Interm.: 30 µg/m^3 Chronic: 8 µg/m^3 EPA Unit risk: 1.3x10^{-5} per µg/m^3 CREL: 9 µg/m^3	Pungent/ 1 mg/m^3
Acetaldehyde/ 75-07-0	Wood products, tobacco, vehicle exhaust	Irritation	RfC: 9 µg/m^3 Unit risk: 2.2x10^{-6} per µg/m^3 CREL: 140 µg/m^3	Pungent, fruity/ 336 µg/m^3
Benzaldehyde/ 100-52-7	Foods, fragrance, detergents, industrial processes, solvents, combustion	Irritation, CNS	WEEL: 8700 µg/m^3 TWA	
Hexanal/ 66-25-1	Flavoring; perfumes; industrial processes for plasticizers, rubber chemicals, dyes, synthetic resins, insecticides; plant sources	Irritation		Grass, fruity/ 57 µg/m^3
Heptanal/ 111-71-7	Flavoring, perfumes, pharmaceuticals, industrial processes; plant and animal sources	Irritation		Fatty pungent odor, fruity
Octanal/ 124-13-0	Perfume, flavoring, industrial processes; plant sources	Irritation		Fruity/ 7.3 µg/m^3
Nonanal/ 124-19-6	Cosmetics, flavoring; plant sources	Irritation		Rose-orange/ 13 µg/m^3
Decanal/ 112-31-2	Flavoring; essential oils	Irritation		
Dodecamethyl-cyclohexasiloxane/ 540-97-6	Cosmetics, paints, varnishes, surface treatments, cookware, health-related products, electronics	No human reports		Odorless
Decamethyl-cyclopentasiloxane/ 541-02-5	Hair preparations, antiperspirants, cosmetics, industrial processes; waste incineration, other industrial sources	No human reports	10 ppm TWA (151 mg/m^3)	

INFORMATION ON SELECTED VOLATILE ORGANIC COMPOUNDS AND CARBONYLS

Chemical/CAS#	Uses/Sources	Health Effects	Health-based Inhalation Screening Guidelines*	Odor/threshold
1-chlorooctane/ 111-85-3	Industrial processes	CNS effects		
Tetradecane/ 629-59-4	Solvent, industrial processes, vehicle exhaust, landfills; natural sources	CNS depression; cardiac arrhythmias		Odorless
n-Hexane/ 110-54-3	Solvent, industrial processes, oil, natural gas	CNS effects	RfC: 0.7 mg/m^3 Chronic MRL: 0.6 ppm (2.1 mg/m^3) CREL: 7000 µg/m^3	Gasoline-like/ 460 mg/m^3
Tetrahydrofuran/ 109-99-9	Solvent; industrial processes	Irritation	PEL: 590 mg/m^3 REL: 590 mg/m^3 TLV: 150 mg/m^3	Faint fruity/ 60-150 mg/m^3
2,2,4-trimethyl-1,3-pentanediol/ 144-19-4	Industrial processes, inks, surface coatings, resins, lubricants	Irritant		
Acetone/ 67-64-1	Solvent, industrial processes, paints, adhesives, cosmetics	Irritation; upper respiratory effects	MRL: Acute: 26 ppm Interm.: 13 ppm Chronic: 13 ppm (31 mg/m^3)	Fruity/ 50 mg/m^3
Methylene chloride/ 75-09-2	Solvent, industrial processes, paint remover, degreaser	Irritation; CNS effects	MRL: Acute: 0.6 ppm Interm.: 0.3 ppm Chronic: 0.3 ppm (1 mg/ m^3) CREL: 400 µg/m^3 Unit risk: 4.7x10^{-7} per µg/m^3	Sweet, chloroform- like/ 500-800 mg/m^3
Phenol/ 108-95-2	Disinfectant; antiseptic, anesthetic; industrial processes	Irritation; upper respiratory effects; CNS effects	CREL: 200 µg/m^3	Acrid/ 180 µg/m^3
D-Limonene/ 5989-27-5 Limonene/ 138-86-3	Flavorings, fragrances, cosmetics, solvent, insecticide, insect repellant; fruits, trees, and other plants	Irritation; skin sensitization	WEEL: 30 ppm TWA (170 mg/m^3)	Lemon, citrus/ 2447 µg/m^3

*PEL: Occupational Safety and Health Administration Permissible Exposure Limit
REL: National Institute for Occupational Safety and Health Recommended Exposure Limit
TLV: American Conference of Governmental Industrial Hygienists Threshold Limit Value
CREL: California Office of Environmental Health Hazard Assessment Chronic Reference Exposure Levels
WEEL: American Industrial Hygiene Association Workplace Environmental Exposure Level
RfC: Environmental Protection Agency Reference Concentration
MRL: Agency for Toxic Substances and Disease Registry Minimal Risk Level

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