NASA/TM-20240000101 (Corrected Copy)

Exposure Limits for Hydrogen Sulfide in Spaceflight

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January 2024

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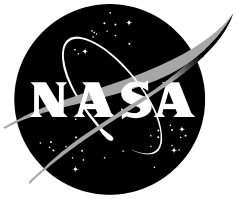

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Acknowledgments

We would like to acknowledge coordination of a panel of external expert reviewers by the Office of the Chief Health and Medical Officer. These external experts provided substantive input and contributed to the development and justification of these limits.

An error in calculations for the 30-day SMAC derivation was noted and corrected. The calculation approach listed remains accurate, but the derived value was changed from 5.7 ppm (8.0 mg/m3) to 1.9 ppm (2.6 mg/m3). The application of the slightly more conservative 7-day values remains applicable.

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ABSTRACT

Hydrogen sulfide (H_2S) has not historically been detected in spacecraft, but the possible evolution of volatile components from polar ice on the lunar surface is a potential concern for NASA's planned Artemis missions. Numerous case reports and occupational epidemiological studies document that exposure to H_2S at high concentrations has effects on the respiratory system, potentially leading to unconsciousness followed by debilitating neurological effects. Studies in rodents demonstrate sensitivity of the respiratory system to lower concentrations of H_2S. Adverse respiratory effects have also been indicated in workers chronically exposed to H_2S. The objective of the present publication is to develop Spacecraft Maximum Allowable Concentrations (SMACs) for H_2S for all current standard durations of exposure for spaceflight (1-hour, 24-hours, 7-days, 30-days, 180-days, and 1000-days). Summary sources and literature review were used to identify relevant studies to inform SMAC development. Space flight mission specific activities and most probable exposure scenarios were used to determine the relevant toxicity endpoints and supporting studies. SMACs were established for hydrogen sulfide of 5 ppm for 1-hour, 1.3 ppm for 24-hours, 1.3 ppm for 7-days, 1.3 ppm for 30-days, and 0.3 ppm for 180-days. Data are not sufficient currently to establish a 1000-day SMAC value. SMACs for H_2S will support development of handling protocols and proper containment for lunar sample collection.

KEY WORDS: hydrogen sulfide; toxicity; spaceflight; lunar volatiles

INTRODUCTION

Hydrogen sulfide (H_2S) acts as an endogenous signaling molecule and exhibits some potentially beneficial therapeutic effects (Szabo, 2007; 2019). Yet, at elevated levels H_2S is highly toxic. Gaseous H_2S continues to be one of the most common hazardous substances attributed to acute poisoning deaths in occupational settings. H_2S is corrosive, explosive (at 4.3–45% by volume in air), and flammable (260°C ignition temperature). H_2S possesses the characteristic smell of rotten eggs, and humans can typically smell H_2S at low concentrations in the air, between 0.0002 and 0.3 ppm, lower than the most sensitive portable monitoring equipment available (ATSDR, 2016). The gas is slightly heavier than air with a specific gravity of 1.2 and a molar mass of 34 g/mol. Consequently, the highest risk of exposure terrestrially is in enclosed spaces.

As a key component of the sulfur cycle, H_2S can be produced naturally in the environment through the anaerobic breakdown of sulfate by bacteria, anthropogenically by a variety of industrial practices, and by degradation of sulfur-containing protein in mammals (ATSDR, 2016). H_2S has industrial applications in a variety of sectors. It is used to make sodium sulfide, sodium hydrosulfide and sulfuric acid. These compounds are then used in the production of dyes, pesticides, and pharmaceuticals. H_2S also has roles to play in metallurgy, laboratory settings, and agriculture (ATSDR, 2016). The nuclear energy sector utilizes H_2S in large quantities to separate “heavy water,” containing the hydrogen isotope deuterium, from regular water. (NRC, 2010)

As missions and exploration efforts venture into permanently shadowed regions at the Moon’s poles, exposure to volatile gasses becomes a more likely scenario for the crew. Volatiles, like H_2S, sequestered in a condensed “ice” phase are very stable in these regions. The presence of ice and the capacity to sublime volatile gasses trapped in the ice has been indicated for the lunar surface (Colaprete et al., 2010; Schultz et al., 2010; Haynes et al., 2010; Gladstone et al., 2010). Although uncertain, these lunar volatiles are thought to arise from sources such as comet and asteroid impacts, solar wind protons, and outgassing from the lunar interior (Hayne, 2018). As such, samples returning from the lunar surface could contain volatile gases like H_2S which could accumulate in the habitable volume of the cabin atmosphere creating a unique exposure scenario for crewmembers.

Acute exposure guidelines for H_2S have been developed by several regulatory and nongovernmental organizations primarily based on experimental animal studies (Table 1). In the United States, safety values for H_2S have been promulgated by the U.S. Environmental Protection Agency (EPA), the Food and Drug Administration (FDA), and the Occupational Safety and Health Administration (OSHA). OSHA sets limits in industries where H_2S is found over the threshold quantity of 1,500 pounds (680 kg). Additional national organizations such as the Agency for Toxic Substances and Disease Registry (ATSDR), National Institute for Occupational Safety and Health (NIOSH), and the American Conference of Governmental Industrial Hygienists (ACGIH) also provide recommended exposure limits.

The health effects of H_2S exposure increase sharply with dose, ranging from respiratory, eye, and throat irritation (20-100 ppm), to olfactory fatigue and nerve paralysis (100-200 ppm), pulmonary edema (300-500 ppm), and coma and death (500-1000 ppm). Most deaths have occurred in industrial settings. These effects all occur above the odor threshold for recognition of H_2S (0.01-0.3 ppm).

Two major effects of H_2S exposure in humans are inflammation and irritation of the mucous membranes, including eyes and respiratory tract from direct action of H_2S on tissues, and systemic toxicity which can result in death at higher acute concentrations. Death would result from paralysis of the respiratory centers of the brain causing respiratory failure and subsequent asphyxia and cardiac failure. However, this can be abated, and the patient may recover if removed from the exposure and artificial respiration is initiated before the heart stops. Systemic intoxication occurs only when the amount of H_2S in the blood exceeds that which can be detoxified and/or eliminated.

METHODS

Summary sources were utilized to gather baseline information and supplemented with a literature search. The literature search was conducted using the phrases “hydrogen sulfide” and “hydrogen sulfide toxicity”. The search was broadened by including more specific terms such as human, animal, respiratory, and CNS primarily in PubMed/Medline. Spaceflight Maximum Acceptable Concentration (SMAC) values were developed using the most relevant and robust study data. Appropriate uncertainty factors were applied to the study points of departure established from the published literature. Spaceflight-associated effects expected to alter H_2S-related effects were considered and applied in the calculations.

TOXICOKINETIC – TOXICODYNAMIC CONSIDERATIONS

Absorption, Distribution, Metabolism, and Excretion

H_2S is absorbed through the skin, lung, and digestive tract lining. The lung is the primary route of absorption. The potential of a gas to reach the deep lung is inversely proportional to its solubility in water, so insoluble gases such as H_2S penetrate to the alveoli at relatively higher concentrations. Diffusion across the alveolar-capillary barrier and dissociation occur almost instantaneously.

Within the body, H_2S is metabolized by oxidation, methylation, and reaction with metallo- or disulfide-containing proteins (Dorman et al., 2002). Once absorbed, H_2S dissociates in part into hydrosulfide ion, then is spontaneously transformed into sulfide and is enzymatically oxidized to thiosulfate, which is oxidized to sulfate and enters general metabolism (Hildebrandt and Grieshaber, 2008; Olson et al., 2013). Some H_2S remains as free H_2S in blood, and this fraction appears to interact with metalloproteins, disulfide-containing proteins, and thio-S-methyltransferase, forming methyl sulfides (Beauchamp et al., 1984).

Results from animal inhalation studies indicate that H_2S is distributed primarily to the brain, liver, kidney, pancreas, and small intestine. Sulfides have been found in the liver, blood, lung, brain, spleen, and kidney of humans following accidental inhalation exposure. The concentration of sulfide in blood rises and is carried to target tissues that, in the case of brain, are already high in sulfide. Because sulfide is cleared so quickly, the concentration rapidly returns to physiologic levels when exposure ceases. Consequently, nonlethal cases do not demonstrate elevated sulfide in blood or tissue for long enough to be useful in exposure assessment or diagnosis. However, sulfide accumulation in tissue can be used as one marker, together with thiosulfate, of exposure postmortem because circulation stops. The sulfide ion binds to heme compounds, but there is no evidence that this is toxicologically important.

In the blood, the gas is associated with alkali sulfide, and the hydrosulfide anion is excreted via exhalation and urine. Sulfate is excreted by the kidney or recycled in intermediary metabolism (Kage et al., 1992). H_2S does not accumulate in the body as it its rapidly oxidized to sulfate, which is readily excreted by the kidneys primarily as sulfate in the urine.

Mechanism of Action

Multiple studies have demonstrated the inhibition of cytochrome oxidase activity in tissues after H_2S exposure of experimental animals (Nicholson et al., 1998; Khan et al., 1990; Dorman et al., 2002). This inhibition is implicated in disrupting respiratory and mitochondrial functions in the mammalian brain and other tissues after H_2S exposure in vivo. The current primary toxicological mechanism of H_2S proceeds through the inhibition of mitochondrial respiration via inhibition of mitochondrial Complex IV (cytochrome c oxidase). Consequently, the consumption of O_2 is inhibited, and mitochondrial electron transport and ATP generation is blocked. Nervous and cardiac tissues, which have the highest oxygen demand, are especially sensitive to the

disruption of oxidative metabolism (Amman, 1996; Szabo, 2018). Hydrosulfide binds to cytochrome causing anoxia at the cellular level (Richardson, 1995; Roth et al., 1997). This effect could result in death from respiratory arrest in the central nervous system. H_2S has been shown to inhibit cytochrome c in vitro at physiologically relevant concentrations and inhibit aerobic metabolism even at relatively low levels. In studies designed to explore the use of H_2S in inducing suspended animation on a mouse model, the gas was found to decrease heart rate, cardiac output, and respiratory rate at 80 ppm (Roth, 2005; Volpato, 2008). The effect was rapidly reversed within 10 minutes of H_2S cessation. In healthy, fit human volunteers, H_2S exposure as low as 5 ppm during exercise (30 minutes) is associated with an early shift from aerobic to anaerobic metabolism, as indicated by increasing blood lactate levels, but without any other reported symptoms (Bhambhani et al., 1994; 1996; 1997).

SUMMARY OF TOXICITY DATA

Toxicity from H_2S is characterized by the following features: odor perception followed at higher concentrations by respiratory irritation, olfactory paralysis, conjunctivitis, pulmonary edema, and acute central neurotoxicity known as knockdown. Occupational and protective health values for the general population are based on the prevention of conjunctivitis (eye irritation), knockdown, and respiratory tract irritation. Acute-and chronic-duration studies suggest that the respiratory tract and nervous system are sensitive targets of H_2S.

Respiratory Toxicity

Fiedler et al. (2008) examined the effect of H_2S levels on respiratory function. The participants reported an increase in upper respiratory symptoms (i.e., sneezing, nasal congestion, choking, throat irritation, or nose irritation) and/or lower respiratory symptoms (i.e., shortness of breath, wheezing, chest tightness, chest pain, or coughing) when exposed to 5 ppm H_2S for 2 hours, as compared to the No Observed Adverse Effect Level (NOAEL) of 0.5 ppm H_2S for this study. The anxiety response increased immediately to about 3.5 out of 10 then slowly declined over 2 hours to about 2 out 10 by the end. Ratings in odor intensity, irritation, and unpleasantness also increased with increased concentrations. Moreover, changes in the severity of irritation due to odor significantly affected changes in anxiety ($F = 54.23$; $df = 1, 641$; $p < 0001$). Thus, it appears that the odor of exposure had a significant influence on anxiety reported by subjects.

Jappinen et al. (1990) exposed 10 asthmatic patients to an H_2S concentration of 2 ppm for 30 min and compared respiratory function before and after exposure. They found no significant difference in pre- and post-exposure measures. However, they did report that 3 of the 10 subjects developed headaches during the exposure.

Bhambhani et al. (1994, 1996, 1997) also conducted experiments on the effects of low doses of H_2S on respiratory function. Although the early studies showed inhalation of lower H_2S doses (5 ppm for 30 minutes) had insignificant effects on respiratory function, in the latest study, they found that inhalation of 10 ppm for 30 minutes H_2S inhalation decreased oxygen uptake of healthy adults during exercise in 70-73 % of the subjects with a concomitant increase in blood lactate (no change in muscle lactate). There was no significant change effect on blood oxygen or carbon dioxide partial pressures or oxygen saturation. The oxygen-carrying capacity of blood and oxygen transport were not affected. There was also no significant effect on cardiovascular responses such as heart rate or blood pressure. The lack of change in capacity and transport likely renders the oxygen uptake finding clinically questionable. In any event, the author concluded that at 10 ppm H_2S, aerobic metabolism tends to be inhibited during exercise.

Richardson (1995) compared baseline respiratory function (FEV_1 /FVC) in sewer workers exposed to H_2S to water treatment workers (unexposed to H_2S). There was a statistically significant difference in the mean FEV/FVC values between sewer and water treatment workers

of similar age, height, race and smoking habit. The difference (3.1, s.e.= 1.4) was greatest in workers categorized to the high exposure group. Within the highest H_2S group, sewer workers had the greatest deficit (5.7, s.e.= 2.0).

In earlier studies, Kilburn et al. (1997, 2003) compared respiratory effects (FVC, FEV_1, reported symptoms) of H_2S on workers in a variety of settings to unexposed populations. The Kilburn studies compared 16-19 subjects exposed at work, seven of which previously experienced knock-down/unconsciousness. The unexposed populations were matched form a national list and identified as local unexposed living >3km away from the source or out-of-state. Exposure concentrations varied greatly among the workers included in the study. Acutely exposed workers had meter readings of 10,000 ppm and 328 ppm. Other exposure concentrations were estimated based on their occupational description- 1 to 10 ppm and 25 to 50 ppm. The authors reported strong association between H_2S exposure and neurobehavioral and respiratory effects. Frequency of symptoms was assessed and compared with the unexposed. The unexposed had values near 100% for all tests. For the exposed, balance was impaired by 246%, eyes closed and 159%, eyes open. Simple and choice reaction times were prolonged by 151% and 130%. Visual field performance was decreased to 72% on right and 55% on left. However, there are concerns related to selection bias in these studies as the participants were randomly selected from a list of plaintiffs in lawsuit related to alleged H_2S exposures from animal processing facilities (Inserra et al., 2004).

Rodent studies were conducted in Fischer and Sprague Dawley rats and B6C3F1 mice exposed to H_2S for 6 hours/day, 5 days/week for at least 90 days at concentrations of 0, 10, 30 and 80 ppm. A statistically reduced body weight gain was noted in both sexes and both types of rats at 80 ppm. In the Fischer rat and male Sprague Dawley, the mean body weights were more than 90% of control though not considered biologically significant. Brain weight was significantly reduced in male Sprague Dawley rats at 80 ppm. In all mice, nasal inflammation identified as rhinitis was observed as minimal to mild at 80 ppm in 8 of 9 male and 7 of 9 female mice. Therefore, 80 ppm was determined as the Lowest Observed Adverse Effect Level (LOAEL) with a NOAEL of 30 ppm (CIIT, 1983a, b, c).

In a re-evaluation study of the CIIT rodent samples by Dorman et al. (2004), rats and mice exposed to 0, 10, 30, or 80 ppm H_2S for 6 hours per day, 5 days per week for 91 to 95 days showed reduced feed consumption and reduced body weights, as previously reported by CIIT. Male Sprague Dawley showed an increased incidence of olfactory neuron loss following exposure to 30 ppm and higher H_2S. Rhinitis was again observed in the mice at 80 ppm. Toxic effects not previously reported to the lung epithelium were also observed in both rat strains at 30 and 80 ppm. Hence, a lower LOAEL and NOAEL of 30 ppm and 10 ppm, respectively, were determined for nasal pathology not previously reported in the CIIT studies (Dorman et al, 2004).

Lastly, Brenneman et al. (2000) reported significant concentration-related increases in the incidence and severity of lesions to the nasal olfactory epithelium in rats exposed to H_2S for 6 hours per day, 7 days per week for 10 weeks. Rodent noses were dissected and fixed in formalin and nasal cross sections to evaluate the major structures and mucosae of the nasal cavity. This study was conducted to evaluate the nasal cavity for exposure related lesions for translation to human dysosmia/anosmia. The effects consisted of olfactory neuron loss and basal cell hyperplasia in rats exposed to 30 or 80 ppm. No adverse effects were observed at 10 ppm. Findings in Brenneman et al. (2002), identified a single three hour exposure to 80 ppm or higher produced nasal lesions, epithelial regeneration and olfactory necrosis. However, the NOAEL for the three-hour exposure for five days was 30 ppm. No lesions were reported at 30 ppm for the 1day or 5-day exposures.

Neurotoxicity

Fiedler et al. (2008) examined the relationship between H_2S levels and cognitive test results before and after exposure. Healthy non-smokers were administered doses of H_2S at 0.05, 0.5, and 5 ppm for 2 hours per each dose. No trends with exposure levels were observed for

cognitive measures, including finger tapping and simple reaction time, but complex reaction time and verbal learning were significantly lower during exposure. A marginal trend was observed for total List A recall with a somewhat larger effect of exposure in the 0.05 and 0.5 ppm conditions. Total List A recall, recall of List A after presentation of the interfering List B and recall of List A after a 30-min delay were all significantly worse during exposure, illustrating a significant time effect. This time effect appears to be more obvious for the 0.05 and 0.5 ppm conditions versus the 5 ppm condition. These data are consistent with a threshold effect of H_2S as low as 0.05 ppm. Although this effect was not consistent with other neurobehavior measures, reduced verbal memory performance and delayed match to memory task have been reported previously. (Inserra et al 2004 and Kilburn et al 1999).

The participants reported increased anxiety during the 5 ppm exposure. The authors related this to odor irritation. The authors also note the subjects' fatigue or lapse in the ability to maintain attention to the material during the exposure period rather than H_2S exposure could account for the reduced verbal learning finding. However, separate post hoc covariance analyses controlling for self-reported fatigue, drowsiness and concentration did not change the statistical significance for verbal learning. The authors concluded that further investigation is needed to determine whether the significant effects are due to H_2S or subject fatigue.

A study of sewer maintenance workers in Egypt by Farahat and Kishk (2010) investigated cognitive impairment due to H_2S exposure. The average H_2S exposure level of the workers was 4.8 ppm (range = 5 to 6.6 ppm). They found that exposed workers had significantly prolonged reaction times and performed worse on neuropsychological tests compared to unexposed workers. However, these findings may be confounded by other possible chemical exposures (e.g, chlorine dioxide, sodium nitrate) and biological hazards (e.g. bacteria).

In earlier studies, Kilburn et al. (1997, 2003) compared neurobehavioral functions (e.g., simple reaction, balance sway speed) in workers exposed to H_2S in a variety of settings to unexposed populations. The studies consistently observed strong associations between H_2S exposure and CNS and respiratory outcomes (highlighted above). In a study of people exposed to H_2S by working in sewer plants, oil refineries, natural gas production plants, and cheese manufacturing plants, Kilburn et al. (2010, 2012) conducted the same battery of neurophysiological and neuropsychological tests. The study reported that people exposed in their work environments had significantly more abnormalities in neurobehavioral functions than control populations from the same town or a neighboring state. The exposed workers also had poorer results on a variety of cognitive tests. There are concerns related to selection bias in these studies as the participants were randomly selected from a list of plaintiffs in H_2S community investigation lawsuit (Guidotti, 2010; Lim, 2016).

SUMMARY OF SMAC DEVELOPMENT

Derivation of 1-Hour SMAC

Human data are adequate to establish a limit for acute exposure. In the series of studies conducted by Bhambhani et al. and reported by ACGIH (2010), exposures at 5 and 10 ppm H_2S for 30 minutes resulted in measurable but "clinically" insignificant changes for decreased oxygen uptake during exercise. However, given the reports of increased anxiety following 2-hr of exposure at 5ppm (Fiedler et al. 2008) and the desire for crew to respond calmly and appropriately in an off-nominal scenario, we conservatively set the provisional 1-hr SMAC limit for H_2S at **5 ppm (7 mg/m^3)**. This is approximately 5-fold lower than the 1-hr AEGL-2 (NRC 2010). 5 ppm is also the ACGIH short-term exposure limit (STEL).

Derivation of 24-Hour SMAC

The proposed 24-hour SMAC is derived using the Brenneman et al. 2002 acute study where a single three-hour exposure to 80 ppm produced nasal lesions in rats. Therefore, a rodent NOAEL of 30 ppm from this study is selected for respiratory effect with an adjustment for interspecies differences. An uncertainty factor of 3 versus 10 is selected as H_2S is a direct contact irritant, rodents are a more sensitive species than human and the -olfactory exposure response is similar for these species. An adjustment for exposure duration for 24 hrs results in a value of 1.3 ppm. This value agrees with the ACGIH TWA and is 3 times lower than the Navy submarine (the nearest analog to spacecraft) limit for 24 hours.

30 pm / 3 x 3 hr/24 hr = **1.3 ppm (1.8 mg/m^3)** (1)

- NOAEL: 30 ppm (measured concentration)
- UF for interspecies differences: 3
- Duration adjustment: 3 hours/24 hours

Derivation of 7-Day SMAC

A rodent NOAEL of 10 ppm is selected for olfactory neuron loss following 6 hours/day, 5 days/week for 90-days inhalation exposure (Dorman et al., 2004). An uncertainty factor of 3 is applied for extrapolation from animal to human. Since the total duration of exposure for the animals was greater than 7 days of continuous exposure (168 hr), no duration adjustment is required.

10 ppm / 3 = 3.3 ppm (4.6 mg/m^3) (2)

- NOAEL: 10 ppm (measured concentration)
- UF for interspecies differences: 3

This value exceeds the 24-hour limit. Hence the 24-hour SMAC of **1.3 ppm (1.8 mg/m^3)** will be applied directly for the 7-day limit since it will also be protective of the longer-term effects.

Derivation of 30-Day SMAC

A rodent NOAEL of 10 ppm is selected for olfactory neuron loss following sub chronic inhalation for 6 hours/day for 7 days/week for 10 weeks (Brenneman et al., 2000). The NOAEL was adjusted for exposure duration and an interspecies factor of 3. results in a concentration of 1.9 ppm.

10 ppm / 3 x (420 hrs/720 hrs) = 1.9 ppm (2.6 mg/m^3) (3)

- NOAEL: 10 ppm (measured concentration)
- UF for interspecies differences: 3
- Duration adjustment: 420 hours/720 hours

This value exceeds the 7-day limit. Hence the 7-d SMAC of **1.3 ppm (1.8 mg/m^3)** will be applied directly for the 30-day limit since it will also be protective of the longer-term effects.

Derivation of 180-Day SMAC

The NOAEL of 10 ppm for olfactory neuron loss in the subchronic rodent study by

Brenneman et al. (2000), is selected as the point of departure for deriving the 180-day SMAC. The study durations 6 hours/day for 7 days/week for 10 weeks. An interspecies uncertainty factor of 3 and a duration adjustment to continuous exposure for 180 days results in a value of 0.3 ppm.

10 ppm / 3 x (420 hrs/4320 hrs) = **0.3 ppm (0.5 mg/ m^3)** (4)

- NOAEL: 10 ppm (measured concentration)
- UF for interspecies differences: 3
- Duration adjustment: 420 hours/4320 hours

Derivation of 1000-Day SMAC

Numerous chronic exposure studies in workers are available in the published literature. However, none are suitable for deriving the 1000-day SMAC. The studies are limited by poorly reported exposure levels, lack of monitoring data, or concomitant exposure. The rodent study used for the 180-d SMAC is also insufficient to establish a 1000-d SMAC. Therefore, at this time, a 1000-d SMAC value will not be set due to a lack of long-term exposure data.

CONSIDERATIONS FOR SPACEFLIGHT ASSOCIATED FACTORS

Spaceflight Factors

Spacecraft operate at CO_2 levels between 2.3 - 5.3 mm Hg. These levels are higher than ambient outdoor CO_2 levels on Earth, 0.23 mm Hg (NASA, 2021). It is reasonable to consider and account for adverse health effects including CNS effects which may occur at levels lower than anticipated with concomitant exposure to H_2S. There exists suggestive evidence for a dose-response association between exposure to CO_2 and H_2S. Donham et al. (1984) reported decrements in lung function following a 4-hour work period in swine confinement facility workers. These workers demonstrated statistically significant declines in pulmonary function, ranging from 3.3% (mean FVC) to 11.9% (mean FEM_{25-75}). The air was concurrently sampled for particulates and gases during the work periods. The result of this study suggests these workers experience respiratory irritation manifested by decreased pulmonary function. However, there was no examination of interactions between concomitant exposure to CO_2 and H_2S. Associations examined were for CO_2 and lung function and H_2S and lung function. Neither relationship was statistically significant. The lack of clear evidence of association deems this interaction as suggestive only. Application of the spaceflight safety factor based on Donham et al 1984 is not justified.

Limitations

Many of the sub-chronic and chronic duration studies in humans are limited by poorly reported exposure levels, lack of monitoring data, or concomitant exposure. Follow-up studies in worker populations exposed to H_2S should be considered. Further investigation into the chronic toxicity endpoint for respiratory and neurotoxicity particularly following inhalation exposure in laboratory animals are needed to determine the possible effects in humans.

CONCLUSIONS

Spaceflight presents a unique environment i.e., microgravity, elevated CO_2, continuous exposure for limited duration (7d–6mo), completely enclosed environment and lack of escape, emphasizing the need for SMACs to be established for standard spaceflight duration exposures

to H_2S. The final spacecraft maximum allowable concentrations for H_2S are given in Table 2. These values were based largely on toxicity to the nasal and respiratory tract. The SMACs were set to protect crewmembers from the adverse effects of acute and chronic exposure to H_2S associated respiratory tract irritation and possibly lung function decrement.

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Table 1. Exposure Limits for H_2S

Organization	Limit	Type	Concentration	Duration
ACGIH	TLV	TWA	1 ppm	8 hrs/day 40 hrs/week
ACGIH	TLV	STEL (TWA)	5 ppm	15 mins 4x/day
NIOSH	REL	Ceiling	10 ppm	10 mins
OSHA	PEL	Peak	10 ppm	
NRC	AEGL-2		27 ppm	1 hr
Navy	EEGL		10 ppm	1 hr
Navy	EEGL		2.8 ppm	24 hr
Navy	CEGL		0.8 ppm	90-day
EPA	RfC	Inhalation	0.003 ppm	daily/lifetime
NIOSH	IDLH		100	

Table 2. Summary of SMAC values for H_2S and major organ toxicity

H_2S					
1-hour SMAC	24-hours SMAC	7-days SMAC	30-days SMAC	180-days SMAC	1000-days SMAC
5 ppm Odor Irritant	1.3 ppm Respiratory Toxicity	1.3 ppm Respiratory Toxicity	1.3 ppm Respiratory Toxicity	0.3 ppm Respiratory Toxicity	No Value Set