Published in final edited form as:

J Agric Saf Health. 2017 November 20; 23(4): 265–279. doi:10.13031/jash.12530.

Evaluation of Low-Cost Hydrogen Sulfide Monitors for Use in Livestock Production

J. M. Beswick-Honn, **T. M. Peters**, and **T. R. Anthony**

Department of Occupational and Environmental Health, University of Iowa, Iowa City, Iowa

Abstract

Direct-reading gas monitors warn workers of the risk of potentially fatal hydrogen sulfide (H_2S) exposures that may arise during manure handling. Low-cost, low-maintenance H_2S monitors are available from many manufacturers, but differences in their features and performance make selection challenging for farmers. Moreover, little information is available on the practical maintenance and performance of these devices in agricultural environments. The objective of this study was to provide information to agricultural workers to aid in the selection, maintenance, and use of low-cost H_2S monitors. This laboratory study evaluated the performance of several low-cost monitors over a simulated period of use of one year in a swine barn. Four models were exposed to H_2S concentrations of 1 to 10 ppm over 18 weeks to examine the drift in reported concentration and changes in the alarm reaction time. Over the simulated barn year, the performance of alarm-only monitors declined faster than that of monitors displaying the H_2S concentration. Of concern was the high-level (20 ppm) alarm failures after an equivalent of 139 days (Altair) and 289 days (BW Clip) in a swine barn, well within the monitor's reported shelf-life. Models displaying concentration exhibited fewer failures but were inaccurate in the displayed concentration when challenged with 20 ppm of H_2S. The T40 Rattler provided consistently higher readings (+2.3 ppm), and the Pac 3500 showed consistently lower readings (−3.4 ppm) when challenged with 20 ppm. This study confirms the need for routine bump tests for these low-cost monitors to ensure that the monitor reacts to the presence of H_2S, even if the manufacturer does not recommend this procedure. Most importantly, agricultural workers should inspect and bump test these monitors prior to any potentially high-risk activity, such as manure agitation, pumping, or pressure washing, to ensure that the monitor appropriately detects and warns users.

Keywords

Calibration; Direct-reading monitors; H_2S; Hydrogen sulfide monitors; Manure gas; Safety; Sensors

Introduction

Agricultural workers continue to be exposed to fatal hydrogen sulfide (H_2S) concentrations during manure handling activities (Adekoya and Myers, 1999; Hendrickson et al., 2004;

Corresponding author: T. Renée Anthony, CPHB, 145 N. Riverside Drive, Iowa City, IA 52246; phone: 319-335-4429; renee-anthony@uiowa.edu.

Beaver and Field, 2007; Riedel and Field, 2013). Livestock operations generate and store large quantities of manure, and its anaerobic decomposition generates H_2S. When manure is undisturbed, background H_2S concentrations in surrounding areas remain low, typically at or below 1 part per million (ppm) (Swestka, 2010; Reeve et al., 2013; Anthony et al., 2015; Guarrasi et al., 2015). However, when manure is agitated during pressure washing or prior to manure pumping, H_2S is released, presenting substantial risk of illness or death (Donham et al., 1982). When the manure is agitated to improve the pumping needed to empty storage pits, H_2S concentrations can rise within seconds to higher than 500 ppm (Donham et al., 1982) and have been observed well over 1000 ppm (Popendorf, 1991; Fabian-Wheeler et al., 2017).

The smell of H_2S is highly recognizable and easily detected at low concentrations (~1 ppm), where its "rotten egg" odor is identifiable. Acute exposures to low concentrations of H_2S can lead to headaches, nausea, and dizziness. However, when concentrations reach 100 to 150 ppm and above, olfactory paralysis occurs, preventing detection of H_2S by smell. At concentrations ranging from 100 to 500 ppm, exposure can result in neurological symptoms. When the H_2S concentration reaches 700 to 1000 ppm, exposure can cause rapid unconsciousness, leading to death with just a few breaths, often called "knock-down" (NRC, 2010).

The Occupational Safety and Health Administration (OSHA) has established permissible exposure limits (PELs) for H_2S applicable to workers in general industry, construction, and shipyards (OSHA, 2017). OSHA regulations do not specify H_2S exposure limits for agricultural workers, but exposures to H_2S in livestock operations would be covered by the OSHA general duty clause, which requires that all workers be protected from recognized hazards, and acutely fatal H_2S exposures from livestock manure are well recognized in this industry. The general industry PELs for H_2S were established in 1970 and specify that exposures be maintained below a 20 ppm ceiling across a work shift, although OSHA allows a single exposure to reach 50 ppm for up to 10 min when there is no other exposure (0 ppm) during a shift. For construction and shipyard workers, exposures to H_2S must be maintained below 10 ppm as a full-shift (8 h) time-weighted average.

More recent consensus exposure limits have been established based on current health hazard evidence, irrespective of occupational sector. The American Conference of Governmental Industrial Hygienists (ACGIH) annually publishes threshold limit values (TLVs) (ACGIH, 2017), and the National Institute of Occupational Safety and Health (NIOSH) periodically revises recommended exposure limits (RELs) to protect workers (NIOSH, 2007). These organizations recommend that short-term exposures not exceed a 10 min ceiling of 10 ppm H_2S (NIOSH) and a 15 min average of 5 ppm (ACGIH). In addition, ACGIH recommends that 8 h average H_2S exposures be maintained below 1 ppm (ACGIH, 2017) to protect against chronic diseases. NIOSH also establishes exposure criteria for chemicals that are immediately dangerous to life and health (IDLH), defined as a concentration above which exposed workers must rely on supplied-air respirators for protection to escape a hazardous environment (NIOSH, 2007). For H_2S, the IDLH is currently 100 ppm, a reduction from the pre-1994 recommendation of 300 ppm.

Hydrogen sulfide can be a major component of manure pit gases, which are liberated from manure during agitation prior to pumping and which can occur in the air above poorly ventilated storage spaces. Indoor manure storage spaces typically meet the criteria for confined spaces because of the high probability of lethal concentrations of H_2S combined with limited entry and egress. While U.S. health and safety regulations do not require agricultural workers to conform to either H_2S exposure limits or confined space practices, preventing access to areas with high H_2S concentrations and monitoring the air quality to ensure safe breathing can protect health and save lives.

Direct-reading gas monitors are useful tools for providing real-time warnings to livestock producers. These monitors can rapidly assess the environment and warn workers in real time to leave areas where the H_2S concentration is unsafe. Most commonly, direct-reading monitors for H_2S incorporate electrochemical sensors that detect H_2S through a reaction between the airborne gas and an electrolyte, generating an electrical signal that corresponds to the gas concentration in ppm. The monitor detects the signal voltage, translates it into a concentration value, and triggers an audible alarm if the concentration exceeds a preset threshold. In the past ten years, manufacturers of gas detection equipment have developed and marketed “low-maintenance” or “maintenance-free” monitors that can provide early hazard warnings to agricultural workers at a fraction of the cost of traditional gas monitors.

ASABE and NIOSH have published guidance on the use of gas monitoring equipment in agriculture, including investigating the safety of manure pits prior to entry (ASABE, 2011; NIOSH 1990). However, the use of gas monitors remains rare, with surveys indicating that only 1.3% to 6% of farm operations test the air quality prior to pit entry (Murphy and Manbeck, 2014). Adoption of gas monitors is also low in allied agricultural services, e.g., only 5% of Iowa manure applicators indicated that they have used H_2S monitors, although 31% indicated they might purchase them in the future (ISU, 2016).

Increased use of gas monitors by agricultural workers could provide important protection against toxic exposure to H_2S. Traditional multi-gas monitors ($600 to $5000), often used for confined space entry, may be too costly and difficult for livestock producers to maintain. Low-cost, low-maintenance monitors for H_2S are available from many manufacturers, but differences in their features and performance make selection challenging. Moreover, little information is available on the practical maintenance and performance of these devices in agricultural environments.

This purpose of this study was to identify and evaluate, in a controlled environment, several models of low-maintenance or maintenance-free monitors that can be used as personal alarms to warn of H_2S exposure risks. This study presents an evaluation of the long-term reliability of these monitors in an anticipated worst-case maintenance scenario, i.e., leaving the monitor inside a livestock production building and exposed to low concentrations of H_2S without performing maintenance throughout its useful life.

Methods

Monitor Selection

In summer 2015, low-cost (<$250) personal H_2S monitors marketed as "low-maintenance" or "maintenance-free" were identified. Farm supply catalogs had no gas monitors for sale, so a broader internet search identified single-gas H_2S monitors available through online U.S. retailers. A panel of industrial hygienists reviewed the resulting web searches for monitors described as needing no initial calibration or maintenance. To prioritize the selection, the panel identified models from recognizable manufacturers of robust high-cost equipment. Next, the top-ranked monitors that were available from at least three online retailers were selected for inclusion. Four monitors were selected for evaluation, representing four manufacturers and a range of cost and features (table 1). Two monitors provided "qualitative" information, with displays indicating the remaining monitor life, in months, but not the H_2S concentration. The other two monitors were "quantitative," displaying the H_2S concentration detected in ppm. All monitors had audible and visual alarm warnings at two levels that were preset by the manufacturer.

Experimental Setup

The monitors were placed in a sealed chamber (0.047 m^3 internal volume, submersible enclosure, Part No. 5376K312, McMaster-Carr, Elmhurst, Ill.) and exposed to low concentrations of H_2S over extended periods to replicate storage and use conditions in livestock production operations (fig. 1). Ports in the chamber accommodated power supply, gas delivery, and pressure release. Two monitors of each model were placed inside the chamber: one was fully activated throughout the study (primary), and the other was placed in standby mode (if available) or turned off throughout the study (secondary). The secondary monitor was used to develop storage recommendations for an unused monitor.

Hydrogen sulfide gas (25 ppm H_2S, Praxair, Inc., Danbury, Conn.) was delivered through a port in the top of the chamber (fig. 1). A fan was placed inside the chamber to ensure well-mixed air. Power to the fan and the ToxiRAE reference monitor was supplied through additional ports on the right side of the chamber. The vent port on the left side of the chamber was opened only during chamber charging to prevent pressurization.

The reference H_2S concentration in the chamber was measured with a ToxiRAE Pro EC (RAE Systems by Honeywell International, Morris Plains, N.J.). One-minute averaged concentrations were logged continuously throughout each chamber test. The cumulative concentration (ppm-time) in the chamber was computed from the ToxiRAE readings. To quantify any sensor drift of this reference monitor, the chamber H_2S concentrations were checked at the start and end of each chamber test and daily with two additional reference monitors: an Altair 4X (MSA Safety, Cranberry Township, Pa.) and a VRAE (RAE Systems by Honeywell International, Morris Plains, N.J.). All three reference monitors were calibrated at the beginning of each chamber test (zero, 20 ppm) using calibration gas (34L-428-20, Gasco Precision Calibration Mixtures, Oldsmar, Fla.).

Test Protocol

The test monitors were exposed to H_2S in the test chamber over 24 sequential short-term tests at concentrations above typical concentrations measured in production buildings, but below alarm level (10 ppm), in order to test the drift and longevity of the monitors in a shorter period while in a controlled environment. This method is similar to aerosol monitor tests (Vanderpool et al. 2001; Kenny et al., 2004) used to assess monitor stability and response time (NIOSH, 2012).

The H_2S concentration and exposure duration were established to approximate the environment that a monitor might encounter over a one-year period in a livestock operation. Specifically, the protocol assumed that these monitors might be stored in livestock buildings, where the electrochemical sensors would be exposed to low concentrations of H_2S throughout the year even if not in use, which could degrade the sensors over time. To convert the chamber test conditions to equivalent barn exposure, the cumulative annual exposure of an H_2S monitor in use in a livestock operation was estimated. This assumed a low background concentration typical inside swine production buildings (1 ppm) and added H_2S contributions anticipated from pumping and weekly bump testing, in which a known concentration of gas is applied to the sensor to ensure that it is responding to the gas (table 2). These short-term peaks contribute little to the annual cumulative concentration relative to the continuous, low background exposures in a livestock building. The annual cumulative exposure for a monitor used in the field was estimated to be just over 367 ppm-day, yielding an average daily H_2S exposure of 1.005 ppm over 365 days. The test monitors were subjected to 24 sequential chamber tests to achieve exposure equivalent to the estimated one-year cumulative concentration in the field.

The procedure for each chamber test was to charge the chamber with H_2S gas, allow the H_2S concentration to decay, and then remove the monitors for performance tests. To charge the test chamber, 25 ppm of H_2S was delivered into the chamber until the concentration was just below the low alarm level (10 ppm). During charging, the chamber concentration was recorded at 2 min intervals with the two test monitors with displays (Pac 3500 and T40 Rattler) and the ToxiRAE reference monitor. When the chamber concentration reached approximately 9.5 ppm, the H_2S flow was stopped. The initial chamber concentration was recorded using all three reference monitors (ToxiRAE, VRAE, and Altair 4X), after which all chamber ports were closed.

After charging, the H_2S concentration in the chamber decreased over subsequent days. In phase 1 of this study, the chamber concentration during each chamber test was allowed to decay to ~1 ppm prior to opening the chamber to evaluate monitor performance. Phase 1 lasted 16 weeks, during which a total of 21 chamber tests achieved a cumulative exposure of 273 equivalent barn days (274 ppm-days) for the test monitors. For the first chamber test in phase 1, the chamber was recharged midway through the 5.8-day period (18.5 equivalent barn days); all other phase 1 tests had a single chamber charge. After 21 chamber tests, the test monitors began to show declines in performance, and testing was accelerated. In phase 2, the last three chamber tests included chamber recharging, without chamber opening, when the H_2S concentration decayed to ~5 ppm in order to maintain higher mean concentrations over time. Phase 2 lasted two weeks to achieve an additional 100 equivalent barn days of cumulative exposure.

For each of the 24 chamber tests, when the chamber H_2S concentration decayed to ~1 ppm, the chamber was opened, the monitor performances were checked (bump tested), and the reference monitors were fully calibrated. Each individual chamber test lasted from 3 to 7 days.

Before each chamber test, all primary test monitors were bump tested by applying 20 ppm of H_2S calibration gas to the sensor. Performance data were collected at this time, including time to respond to low and high alarms (all monitors) and concentration readings (T40 Rattler and Pac 3500 only). In addition, the logged data from the ToxiRAE reference monitor were downloaded to compute the cumulative exposure of the monitors in the chamber. The secondary test monitors were not bump tested after each chamber test; instead, they were bump tested only at the end of the study.

After testing began, Honeywell released a BW Clip Real Time (RT) monitor with concentration display that used the same electrochemical sensor as the BW Clip monitor. A BW Clip RT monitor was added to the study at chamber test 14.

Performance Analysis

The cumulative H_2S exposure (ppm-day) of the test monitors was computed from the activation of the test monitor using the ToxiRAE logged concentration data. The cumulative concentration at the end of each chamber test was used to mark changes in test monitor performance. The cumulative concentrations were converted to equivalent time in a livestock building by dividing the chamber concentrations by 1.005 ppm H_2S per day in a barn to compute the equivalent barn days associated with the laboratory tests. Failures were reported in equivalent barn days to indicate when a failure would be anticipated in a typical livestock operation. The equivalent days of barn exposure were identified for each monitor when the high alarm failed to signal at either 60 s (manufacturer's criteria) or 15 s (field recommendation criteria) during bump testing (Wanek, 2011). For the quantitative test monitors (Pac 3500 and T40 Rattler), failure was also identified when the monitor drifted below the calibration gas concentration during bump tests (20 ppm) or differed from the reference monitor by 3 ppm (15% difference).

For the secondary test monitors, which were in standby mode or off throughout the study, these same criteria were used at the end of the study to determine if the concentration had drifted by more than 3 ppm or if the alarm response had failed.

Results

Chamber Concentrations

The test monitors were challenged in the chamber for 373 equivalent barn days. The bump testing of the primary test monitors over the 24 chamber tests was equivalent to field bump testing every two weeks over a one-year period. Figure 2 illustrates the patterns of gas concentration generated to expose the test monitors across the chamber tests. Figure 2a shows the pattern over the entire test period, with phases 1 and 2 delineated. Figure 2b illustrates the concentrations in chamber test 1 (phase 1), with a quick concentration increase to just below the low alarm level (10 ppm) and then a decay to 1 ppm. This first test included a second charging at day 10 (equivalent barn day). Figure 2c illustrates the charging pattern in phase 2, using chamber test 22, to illustrate how higher chamber concentrations were maintained in the last three tests, in which an initial charge to ~9.5 ppm was followed by two additional chamber charges when the concentration decayed to 5 ppm on equivalent barn days 294 and 299.

The ToxiRAE reference monitor, which was used throughout the chamber tests, showed no significant drift over the study period. Linear regression between between the ToxiRAE and both the VRAE and the Altair 4X produced slopes of 1 and intercepts indicating that the ToxiRAE read 0.2 ppm lower, on average, than the other two reference monitors (R^2 = 0.97 to 0.98).

Performance of Primary Monitors

The times at which notable performance failures occurred are shown in figure 3. Over the 18 weeks of chamber testing, the T40 Rattler required battery changes four times. While not considered failures under the study's criteria, these events were noted to determine the higher maintenance requirements of the T40 Rattler. The Altair failed to activate the high alarm nine times during bump tests. The BW Clip experienced a high alarm failure only once during testing after 324 equivalent barn days. These high alarm failures were considered critical because the monitor failed to detect the gas at the high alarm setting within 1 min of gas exposure. The Pac 3500 had 17 events in which the monitor reading was at least 3 ppm (15%) lower than the 20 ppm calibration gas. This 15% underestimation at low concentrations may not be critical, but it could be important at higher, more hazardous concentrations.

The concentrations displayed during bump tests of the quantitative monitors are provided in figure 4. The T40 Rattler read consistently higher than the bump test gas (mean = +2.3 ppm). On equivalent barn day 203, the T40 Rattler read below the 20 ppm challenge concentration, but the battery charge read low soon after this calibration. The reported low concentration with low battery indicates that battery management is critical for using the T40 Rattler in the field. The Pac 3500 consistently read low (mean = −3.4 ppm), with 17 of 22 tests low by more than 15% (3 ppm). The mean difference of 3.4 ppm is equivalent to a drift of 17% from the bump test gas, which might be anticipated after 17 months of field use with the maximum concentration drift reported for the Pac 3500; however, this discrepancy was observed almost as soon as the monitor was turned on. The BW Clip RT, added at chamber test 14, was challenged to only 206 equivalent barn days of H_2S. No alarm failures were noted, and the concentration display did not drop below the 15% criterion (3 ppm) during the bump tests.

Table 3 details the response times required for the primary qualitative test monitors to signal the low (10 ppm) and high (15 ppm) alarms during bump testing. During phase 1, both monitors signaled the low and high alarms quickly, but by equivalent barn day 98, the Altair required 31 s to signal the high alarm. By equivalent barn day 273, the Altair did not activate the high alarm when challenged with 20 ppm of H_2S for more than 60 s. The BW Clip continued to activate the high alarm until day 289, with a recovery on the next test. A noticeably longer response time was clearly developing in the BW Clip at the end of one equivalent year of use.

Performance of Secondary Monitors

The performance of the secondary test monitors was examined at the end of the test period, with bump tests occurring before the chamber studies began and at 273 and 373 equivalent barn days of chamber exposure. The secondary T40 Rattler, which was turned off during the study, passed the alarm tests and displayed 20 ppm, matching the bump test gas. The secondary Pac 3500, also turned off for the chamber tests, reported 2.5 ppm below the calibration gas target, similar to the primary Pac 3500 monitor. The secondary BW Clip was put into hibernation mode at the start of the study using the manufacturer’s hibernation case. The display of time remaining confirmed that it had been hibernating, and the monitor responded adequately to the bump tests (alarm activation and speed). The secondary Altair was incapable of being shut off or hibernating once activated. This secondary test monitor was active throughout the entire chamber test period but was not bump tested between each chamber test. Like the primary Altair, the secondary Altair failed the high alarm test when it was challenged at equivalent barn day 273.

Discussion

Each of the four models of test monitors exhibited a decline in performance over the study. These results confirmed that long-term exposure to even low levels of H_2S might jeopardize the reliability of direct-reading monitors. While the user instructions provided with these monitors indicated that little or no maintenance is needed, bump tests are critical to ensure that alarms function and concentrations are accurate. Based on performance, qualitative observations, features, and manufacturer’s instructions, the ranked order of the recommended monitors is: (1) Honeywell BW Clip, (2) Industrial Scientific T40 Rattler, (3) Dräger Pac 3500, and (4) MSA Altair.

The Honeywell BW Clip monitors (primary and secondary) responded consistently to bump tests for most of the test period. Low alarms (10 ppm) occurred within 10 s for every bump test. This monitor required the least amount of maintenance and exhibited the fewest failures. This monitor also has an ancillary hibernation case (~$15) that extends the life of the monitor, with evidence of this protection demonstrated by the secondary monitor. While the BW Clip RT was only available midway through the study and was tested for only 204 equivalent barn days, it had no failures. This unit uses the same hibernation case and has identical sensor technology as the BW Clip that completed the full test period. Because 89% of recently surveyed livestock producers indicated that concentration display was an important feature of H_2S monitors (Anthony, 2017), the BW Clip RT may be highly attractive for agricultural operations.

The Industrial Scientific T40 Rattler required more maintenance than the BW Clip due to the number of battery changes, but otherwise showed no failures. Although the test gas readings were not accurate, the primary test monitor overestimated the concentrations, erring on the side of worker protection. However, a concern is that the secondary T40 Rattler displayed low concentrations at the end of study. Users can fully calibrate this monitor, allowing adjustment of the reported concentrations to match calibration gas. Due to its vulnerability during low battery charge, new batteries should be installed prior to using this monitor for activities with high risk of H_2S exposure. It is unclear how long the batteries will last when the monitor signals alarms for long periods in the field.

Both Dräger Pac 3500 test monitors displayed concentrations lower than the 20 ppm calibration gas during bump tests at monitor activation and consistently throughout the chamber tests. Under-reporting of the actual concentration is problematic because a hazardous environment might be identified as safe. For industries in which chronic low exposures are monitored and regulated, inaccurately low readings in the range of 20 ppm would be unacceptable. More importantly, this monitor includes a menu-driven bump test feature, not used during the study, that may be problematic in the field because an unsuccessful bump test using the device menu would disable the device, leaving a producer with no functioning monitor should the device read low.

The MSA Altair monitors cannot be turned off after initial activation. According to the manufacturer, the alarm should respond to bump testing within 60 s of gas application, although response in 15 s is recommended (Wanek, 2011). The primary monitor failed to signal an alarm at 20 ppm at 106 equivalent barn days of exposure. Without bump tests to verify its performance, the Altair provides no other indication of failure to the user, which could put a worker in serious danger of exposure. Due to the high failure rate of the Altair in this experiment, this monitor is not recommended for agricultural operations with limited monitor calibration and maintenance programs.

Maintenance Recommendations

The sensors used in the tested monitors have a finite life. Over time, the sensor performance may be reduced due to loss of electrolyte from reactions with H_2S and other gases and from deposition of particles on the diffusion surfaces (Warburton et al., 1998; Woodfin, 1994; NIOSH, 2012; Pandley et al., 2012). Loss of electrolyte results in decreased response to a fixed gas concentration, reducing the ability of the monitor to detect the gas accurately. For this reason, gas monitors should be routinely challenged with a known concentration of test gas to ensure that any changes in the electrical signal over time result in accurate reporting of the gas concentration and trigger appropriate alarms.

According to the manufacturers' documentation for these monitors, none of the monitors require calibration at the time of purchase. Two manufacturers (MSA and Dräger) recommend bump testing their monitors, as performed in this study. The manufacturers recommended that bump testing or other basic checks be performed "according to industry standards" or "according to local protocols" in the documentation. However, the agricultural community has not formally established recommendations for the frequency of these checks. Based on this study's findings, routine (at least monthly) bump testing is recommended for these low-cost monitors during activities of low risk as well as prior to conducting high-risk operations (e.g., manure pumping, pressure washing of swine rooms, testing confined space air quality). Bump testing is recommended well in advance of high-risk activities to verify that the sensor is performing well so that there will be time to calibrate, repair, or replace the monitor if necessary. In addition, due to the performance differences among these monitors when taken out of the box, bump testing is recommended upon first activation of the monitor.

The cost of supplies and expertise needed to test these monitors is not trivial. While each monitor can be obtained for less than $250, calibration gas ($100 and up) and a regulator ($100 to $200) are also needed to perform bump tests. Calibration gas for H_2S typically has a shelf-life of up to 18 months. In small and medium-size operations, the calibration gas may likely expire before it is consumed. Feasible systems for providing technical expertise to bump test and calibrate the monitors, and possibly resources to purchase and maintain calibration systems, may be needed for local farming communities. The need to perform checks of the sensor response must be communicated to the workers who rely on these monitors.

When a monitor is purchased, storage in areas free of H_2S is recommended. While the bump test concentrations reported by the quantitative monitors changed throughout the study period, the readings at the end of the study were the same as at the start. However, the electrolytic solutions may decay in the sensors of the alarm-only monitors studied here. Because manufacturers can change sensor components over time, all sensors need to be protected from H_2S exposure when not in use to maximize their life.

The Altair and BW Clip have internal batteries that are not designed for user changing. Thus, when the battery is dead or the two-year activation period has been reached, the monitor must be replaced. If the alarm was not activated, these monitors would theoretically last the duration of the two-year warranty period. The Pac 3500 has a replaceable lithium battery, and the T40 Rattler uses a single AA alkaline battery. At first glance, the AA battery was identified by farmers as a favorable feature (Anthony, 2017). However, the number of battery changes required for the T40 Rattler during this study could indicate a vulnerability, and particular attention should be given to the battery level to ensure that the monitor remains responsive during use.

Study Limitations

This study did not account for humidity, temperature extremes, or other coexisting contaminants in livestock operations, which could further decrease the accuracy and useful life of the electrochemical H_2S sensors. Temperatures above 25°C have been shown to increase sensor readings by approximately 0.5% to 1.0% per °C (Chou, 2000). Similarly, extremely high humidity can cause condensation to form on the electrode, interfering with the accuracy and operation of the sensor (Chou, 2000). Particle deposition on the sensor or its external filter may also affect the monitor response and should be included in field performance assessments of H_2S monitors. Field use may require replacement of the filter, which might not be possible for all low-cost monitors. Thus, long-term evaluations of these monitors in agricultural environments would provide realistic feedback on how temperature, humidity, dust, and co-contaminants affect the sensors over time.

Although these monitors were challenged at concentrations higher than typical background levels in livestock buildings, the study used equivalent barn exposure assumptions to simulate the performance of each monitor over approximately one year in a livestock barn with a background concentration of ~1 ppm. Under these conditions, both alarm-only monitors showed signs of alarm failure at the high alarm setting and began to show effects at the low alarm level. If the background concentration in a livestock building is higher than 1 ppm, these monitors may show signs of failure even earlier than reported here. This study did not examine how well these monitors perform over time when exposed to concentrations that are immediately dangerous to life and health (100 ppm), both in terms of monitor response and useful life. It is reasonable to recommend bump testing the monitors after exposure to field concentrations that result in alarms.

Finally, this study tested a very small sample of monitors. Only four models were tested, with only two monitors of each model. While this work informs how monitors might perform over a year, it is impossible to determine that any model is significantly better- or worse for agricultural use without additional testing, as sensors and monitors can vary between manufacturer lots. Bump testing initially and throughout the monitor's useful life is standard practice in other industries and, based on findings of this study, is recommended to appropriately inform users of H_2S risks in agricultural operations.

Conclusion

Each of the low-cost H_2S monitors that were studied exhibited performance characteristics indicating that maintenance is needed throughout the monitor's life. Monitors should be challenged with a test gas (bump tests) to ensure that the sensor can detect H_2S concentrations and signal alarms as designed. As shown in this study, bump tests are more important later in the life of the monitor, when the likelihood of failure increases. However, if tested and maintained appropriately, these monitors have potential to warn agricultural workers of potentially deadly H_2S exposures. Future work is needed to determine if environmental factors within a barn would contribute to sensor failure even earlier than identified in these chamber tests. The results of this study can be used in agricultural educational programs aimed at increasing awareness of H_2S exposure risks, where discussions of gas monitor selection and use can incorporate both the benefits and limitations of direct-reading monitors.

Acknowledgments

This research was funded in part by CDC/NIOSH Great Plains Center for Agricultural Health (Grant No. U54 OH007548).

References

ACGIH. TLVs and BEIs based on the documentation of the threshold limit values for chemical substances and physical agents and biological exposure indices Proc American Conf of Governmental Industrial Hygienists. Cincinnati, OH: ACGIH; 2017.

Adekoya N, Myers JR. Fatal harmful substances or environmental exposures in agriculture, 1992 to 1996. J Occup Environ Med. 1999; 41(8):699–705. https://doi.org/10.1097/00043764-199908000-00013. [PubMed: 10457514]

Fonner, RE., editor. Transferring Technologies for Industry, No 6. Beltsville, MD: USDA, Agricultural Research Service, National Agricultural Library, Technology Transfer Information Center; Using sensors to detect potentially hazardous atmospheres in production agriculture.

Anthony, R. Farm Families Alive & Well, 23(2), 1–2. Iowa City, IA: Great Plains Center for Agricultural Health; 2017. Gas monitors on the farm. Retrieved from https://www.public-health.uiowa.edu/icash/wp-content/uploads/2017/03/Alive-Well-Newsletter-March-2017.pdf

Anthony TR, Altmaier R, Jones S, Gassman R, Park JH, Peters TM. Use of recirculating ventilation with dust filtration to improve wintertime air quality in a swine farrowing room. J Occup Environ Hyg. 2015; 12(9):635–646. https://doi.org/10.1080/15459624.2015.1029616. [PubMed: 25950713]

ASABE. EP470.1: Manure storage safety. St. Joseph, MI: ASABE; 2011.

Beaver RL, Field WE. Summary of documented fatalities in livestock manure storage and handling facilities: 1975–2004. J Agromed. 2007; 12(2):3–23. https://doi.org/10.1300/J096v12n02_02.

Chou, J. Hazardous gas monitors: A practical guide to selection, operation, and applications. New York, NY: McGraw-Hill; 2000.

Donham KJ, Knapp LW, Monson R, Gustafson K. Acute toxic exposure to gases from liquid manure. J Occup Environ Med. 1982; 24(2):142–145.

Fabian-Wheeler EE, Hile ML, Murphy DJ, Hill DE, Meinen R, Brandt RC, Hofstetter D. Operator exposure to hydrogen sulfide from dairy manure storages containing gypsum bedding. J Agric Saf Health. 2017; 23(1):9–22. https://doi.org/10.13031/jash.11563. [PubMed: 29140615]

Guarrasi J, Trask C, Kirychuk S. A systematic review of occupational exposure to hydrogen sulfide in livestock operations. J Agromed. 2015; 20(2):225–236. https://doi.org/10.1080/1059924X.2015.1009667.

Hendrickson RG, Chang A, Hamilton RJ. Co-worker fatalities from hydrogen sulfide. American J Ind Med. 2004; 45(4):346–350. https://doi.org/10.1002/ajim.10355.

ISU. Hydrogen sulfide safety. Ames, IA: Iowa State University Extension and Outreach; 2016. Retrieved from http://www.agronext.iastate.edu/immag/info/H2S%20Monitors.pdf

Kenny LC, Merrifield T, Mark D, Gussman R, Thorpe A. The development and designation testing of a new USEPA-approved fine particle inlet: A study of the USEPA designation process. Aerosol Sci Tech. 2004; 39(S2):15–22. https://doi.org/10.1080/027868290502290.

Murphy DJ, Manbeck HB. Confined space manure storage and facilities safety assessment. J Agric Saf Health. 2014; 20(3):199–201. https://doi.org/10.13031/jash.20.10377. [PubMed: 25174151]

NRC. In Acute exposure guideline levels for selected airborne chemicals (Vol. 9, pp. 173–218). Washington, DC: National Research Council; 2010. Hydrogen sulfide acute exposure guideline levels. https://doi.org/10.17226/12978

NIOSH. Publication 90–103. Washington, DC: National Institute for Occupational Safety and Health; 1990. NIOSH alert: Preventing deaths of farm workers in manure pits. Retrieved from https://www.cdc.gov/niosh/docs/90-103/

NIOSH. Publication 2005-149. Washington, DC: National Institute for Occupational Safety and Health; 2007. NIOSH pocket guide to chemical hazards. Retrieved from https://www.cdc.gov/niosh/docs/2005-149/pdfs/2005-149.pdf

NIOSH. Publication 2012-162. Washington, DC: National Institute for Occupational Safety and Health; 2012. Components for evaluation of direct-reading monitors for gases and vapors. Retrieved from https://www.cdc.gov/niosh/docs/2012-162/pdfs/2012-162.pdf

OSHA. Washington, DC: Occupational Safety and Health Administration; 2017. Table Z-2: Air contaminants. 29 CFR 1910.1000, amendment 2017. Retrieved from https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=9993

Pandey SK, Kim KH, Tang KT. A review of sensor-based methods for monitoring hydrogen sulfide. Trends Anal Chem. 2012; 32:87–99. https://doi.org/10.1016/j.trac.2011.08.008.

Poppendorf, W. Gases, vapors, liquids, and drugs. Proc. Surgeon General's Conf. on Agricultural Safety and Health; Washington, DC. National Institute for Occupational Safety and Health; 1991. Retrieved from https://profiles.nlm.nih.gov/ps/access/NNBBWK.pdf

Reeve KA, Peters TM, Anthony TR. Wintertime factors affecting contaminant distribution in a swine farrowing room. J Occup Environ Hyg. 2013; 10(6):287–296. https://doi.org/10.1080/15459624.2013.777303. [PubMed: 23548103]

Riedel SM, Field WE. Summation of the frequency, severity, and primary causative factors associated with injuries and fatalities involving confined spaces in agriculture. J Agric Saf Health. 2013; 19(2):83–100. https://doi.org/http://dx.doi.org/10.13031/jash.19.9326. [PubMed: 23923729]

Swestka, RJ. MS thesis. Ames, IA: Iowa State University, Department of Agricultural Engineering; 2010. Hydrogen sulfide spatial distribution and exposure in deep-pit swine housing. Retrieved from http://lib.dr.iastate.edu/cgi/viewcontent.cgi?article=2440&context=etd

Vanderpool RW, Peters TM, Natarajan S, Gemmill DB, Wiener RW. Evaluation of the loading characteristics of the EPA WINS PM2.5 separator. Aerosol Sci Tech. 2001; 34(5):444–456. https://doi.org/10.1080/02786820117739.

Wanek, R. Monitoring H2S to meet new exposure standards. Dallas, TX: Occupational Health and Safety; 2011. Retrieved from https://ohsonline.com/articles/2011/09/01/monitoring-h2s-to-meet-new-exposure-standards.aspx

Warburton PR, Pagano MP, Hoover R, Logman M, Crytzer K, Warburton YJ. Amperometric gas sensor response times. Anal Chem. 1998; 70(5):998–1006. https://doi.org/10.1021/ac970644y. [PubMed: 21644629]

Woodfin, WJ. NIOSH manual of analytic methods. 4th. Washington, DC: National Institute for Occupational Safety and Health; 1994. Chapter H: Portable electrochemical sensor methods. Publication 94–113Retrieved from https://www.cdc.gov/niosh/docs/2003-154/pdfs/chapter-h.pdf

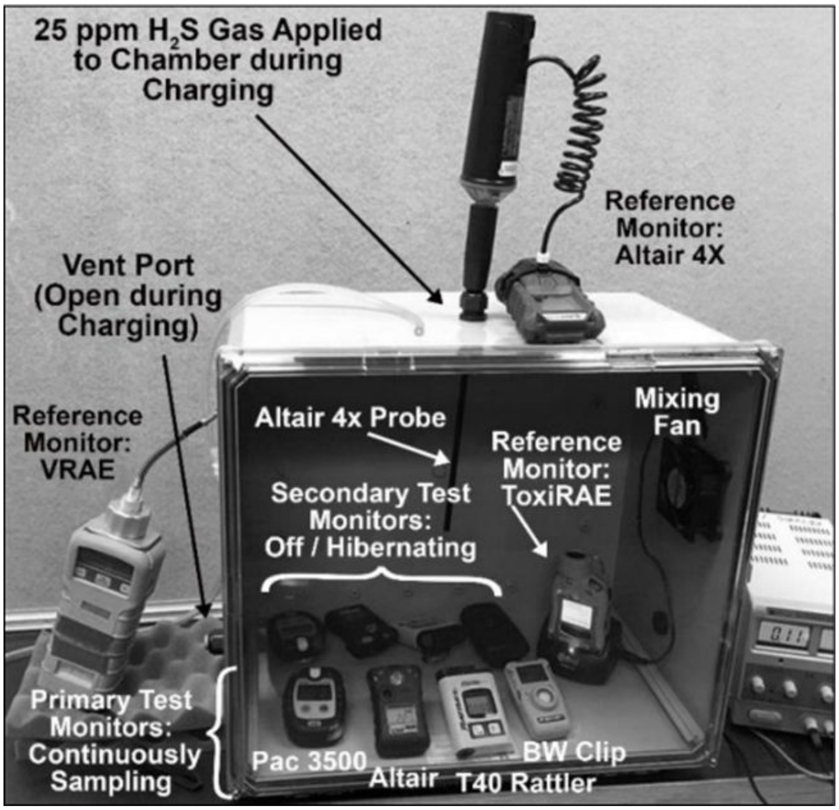

Figure 1.

Experimental setup of test chamber. The primary test monitors that were continuously operating are at the bottom, and the secondary monitors in standby mode are behind them. The ToxiRAE reference monitor logged H_2S concentrations throughout each chamber test, and the probes for the external VRAE and Altair 4X reference monitors were inserted initially and periodically throughout each test to confirm the ToxiRAE readings of the chamber H_2S concentration.

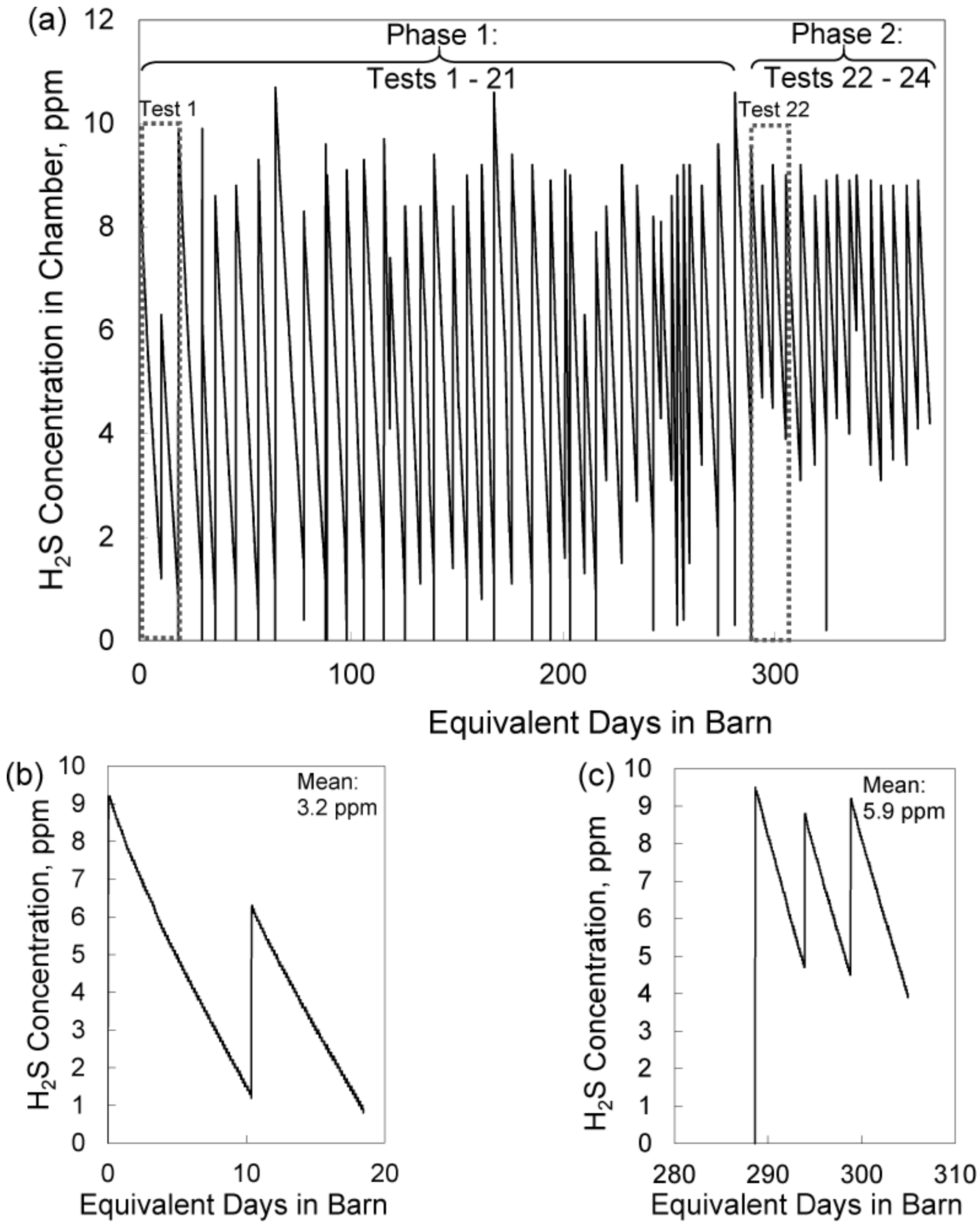

Figure 2.

Pattern of chamber H_2S concentration during (a) entire duration of testing (24 chamber tests), (b) chamber test 1 (phase 1) in which the concentration was allowed to decay to 1 ppm, and (c) chamber test 22 (phase 2) in which the concentration was maintained with recharging. Concentrations were from the data-logging ToxiRAE reference monitor.

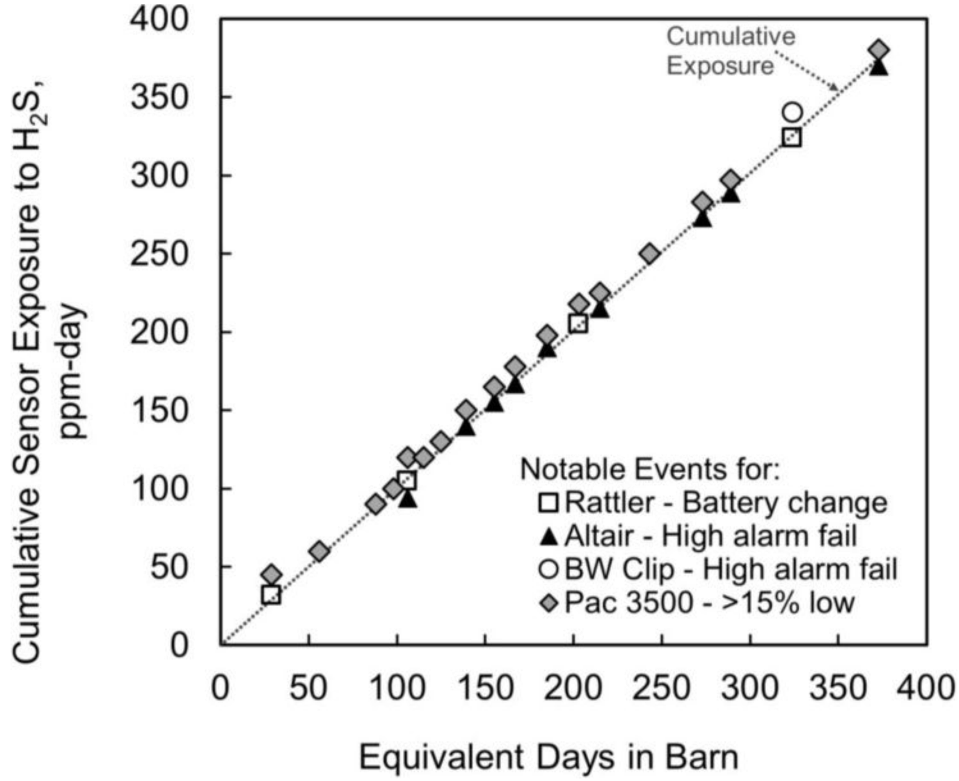

Figure 3.

Test monitor failures during bump testing over the chamber test period by equivalent barn days and by cumulative concentration of monitor exposure (ppm-days).

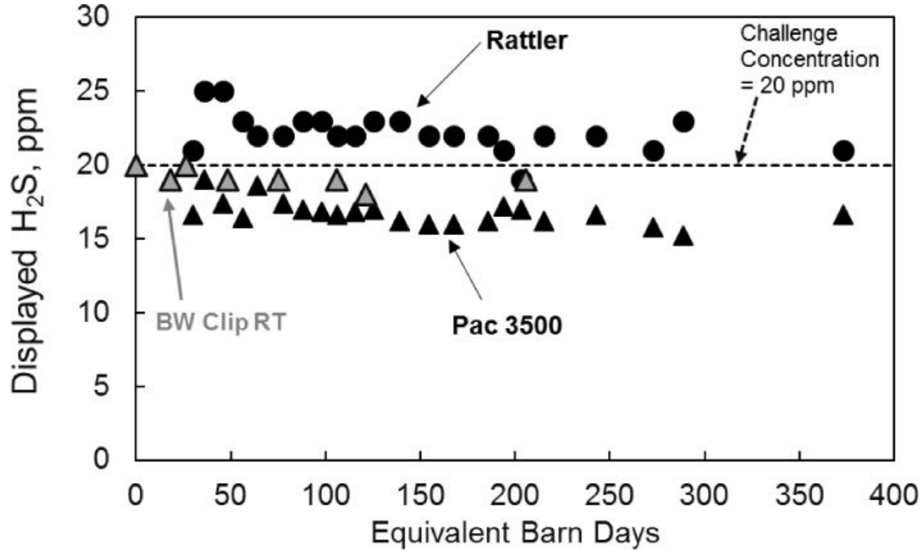

Figure 4.

Concentrations displayed during bump tests of primary quantitative monitors using 20 ppm H_2S challenge gas.

Table 1

Test monitors selected for the study, with comparison of key features.

	Qualitative Monitors		Quantitative Monitors	
Specification	**Altair[a]**	**BW Clip[b]**	**Pac 3500[c]**	**T40 Rattler[d]**
Cost	**$109**	**$110**	**$209**	**$220**
Battery				
Type	Lithium	Internal (2 years)	Lithium	AA (1500 h)
Replaceable	No	No	Yes	Yes
Display				
Concentration	No	No	Yes	Yes
Default low alarm	10 ppm	10 ppm	10 ppm	10 ppm
Default high alarm	15 ppm	15 ppm	20 ppm	20 ppm
Monitor response				
Reported accuracy[e]	NS	NS	≤1% drift per month	NS
Maximum detection	100 ppm	100 ppm	100 ppm	500 ppm
Warranty period	Two years or 18 h alarm	Two years with 2 min alarm per day	Two years	Two years from shipping date
Shelf-life	One year prior to activation	One year prior to activation	Two years	One year prior to activation
Manufacturer recommendations[e]				
Bump test	Recommended	Possible[f]	Recommended	Possible
Calibration	Possible but not required	Recommended if alarmed[f]	Possible[f]	Possible
Concentration	NS	40 ppm	NS	25 ppm
Flow rate	0.25 L min^{-1}	NS	0.5 L min^{-1}	NS

[a]MSA Safety, Cranberry Township, Pa.

[b]Honeywell International, Morris Plains, N.J.

[c]Dräger Safety, Inc., Pittsburgh, Pa.

[d]Industrial Scientific Corp., Pittsburgh, Pa.

[e]As indicated in user manual provided with monitor at time of purchase. NS = not specified in manual.

[f]Requires additional proprietary hardware or software not included with monitor purchase.

Table 2

Estimated annual cumulative H_2S exposure for a monitor stored in a livestock building.

Typical Exposure Source	Concentration (ppm)	Duration and Frequency Assumptions	Cumulative ppm-day
Background concentration in building	1	Constant, 365 days	365
High concentration events	25	15 min, 4 per year	1.04
Weekly bump testing	20	1 min, 52 per year	0.72
		Annual total:	366.76

Table 3

Alarm response of primary test monitors using 20 ppm H_2S calibration gas. “Pass” indicates quick alarm activation, a number indicates the seconds required to signal the alarm when the calibration gas was applied to the sensor, and “Fail” indicates that the alarm did not activate within 60 s.

	Equivalent Barn Days	MSA Altair		BW Clip	
		10 ppm	15 ppm	10 ppm	15 ppm
Phase 1	0	Pass	Pass	Pass	Pass
	30	Pass	Pass	Pass	Pass
	36	Pass	Pass	Pass	Pass
	46	Pass	Pass	Pass	Pass
	56	Pass	Pass	Pass	Pass
	64	Pass	Pass	Pass	Pass
	78	Pass	Pass	Pass	Pass
	88	Pass	Pass	Pass	Pass
	98	Pass	31	Pass	Pass
	106	12	Fail	Pass	Pass
	115	11	49	Pass	Pass
	125	12	40	Pass	Pass
	139	12	Fail	9	12
	155	14	Fail	10	13
	167	12	Fail	9	13
	185	11	Fail	10	18
	194	13	49	10	19
	203	11	42	10	18
	215	10	Fail	10	20
	243	13	49	10	20
Phase 2	273	10	Fail	10	23
	289	12	Fail	11	Fail
	373	16	Fail	12	20