ESTIMATING PHOSPHINE EMISSIONS DURING GRAIN BIN FUMIGATIONS

Executive Summary

To proactively address the rising scrutiny on phosphine emissions, the National Grain and Feed Foundation funded a crucial study by Kansas State University (K-State). This groundbreaking research demonstrated that when grain bins are properly sealed, phosphine fumigation results in no detectable emissions.

Leveraging these robust findings, the National Grain and Feed Association (NGFA) developed comprehensive emission estimates and background documents. These resources, informed by the K-State study, reveal that actual phosphine emissions are significantly lower than estimates from some environmental regulatory agencies, thereby empowering the grain and feed industry to achieve a reduced regulatory burden and lower emission fees.

Contents

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[1] The report and data are as of November 16, 2025.

KANSAS STATE UNIVERSITY | Department of Grain and Food Science

Estimating Phosphine Emissions during Grain Bin Fumigations

Final report

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Funded by:

National Grain and Feed Foundation

Project Outline

Purpose:
Evaluate phosphine concentrations during grain bin fumigation.

Objectives:
• Assess external phosphine leakage
• Quantify internal phosphine concentrations
• Examine vertical gas distribution

Methodology

An in-house fumigation trial was conducted to assess external phosphine emissions and internal gas distribution during fumigation of a steel grain bin. The trial served as a preparatory step for a full-scale fumigation with a commercial fumigation contractor.

The fumigation was performed in a U.S. SCAFCO grain silo, Model 1503HBT, with a diameter of 4.57 m, peak height of 7.73 m, and internal volume of 71.9 m^3, corresponding to a wheat capacity of approximately 1650 bushels. The time of fumigation was at 12:45 pm. The fumigant was Degesch Phostoxin (55% aluminum phosphide) applied as eight foil pouches, with the total dose selected to approximate the maximum label rate on a volume basis. Phostoxin pouches were introduced from the top access hatch and distributed over the grain surface following product handling guidelines.

Table 1. Specifications of the U.S. SCAFCO grain silo

Specification	SCAFCO Grain Systems Model 1503HBT
Diameter	4.57 m (15.0 ft)
Peak height	7.73 m (25.3 ft)
Volume	71.9 m^3 (2539 ft^3)
Wheat volume	1650 bu.

Phosphine concentrations were monitored using a calibrated Dräger X-am 5000 gas detector equipped with dual-range phosphine sensors (0–20 ppm and 0–2000 ppm), enabling measurement of both low and high concentrations in air. Sixteen external measurement points were established around the silo at a uniform height of 5 ft (1.52 m) above ground to evaluate gas leakage. These points were arranged along eight evenly spaced radial directions, with two distances from the bin wall in each direction: 1 m and 2 m, providing near-field and mid-field coverage.

Internally, three concentration-monitoring cables were installed vertically in the geometric center of the bin. Sampling inlets along these cables corresponded to three nominal heights from the bottom: bottom (1.0 m above the bin bottom), middle (4.0 m), and top (7.5 m, near the grain surface). These positions allowed characterization of vertical stratification of phosphine within the grain bulk and headspace.

Phosphine measurements were collected over a 5-day fumigation period. External and internal concentration monitoring points were checked once per day until day 5. Internal results are presented as whole-bin mean concentrations and as values at the three cable heights.

Results and Discussion

i. External Leakage Monitoring

Across the 5-day fumigation period, phosphine concentrations at all 16 external monitoring points remained below the instrument detection limit (0 ppm recorded at all readings). This outcome indicated that the bin maintained effective containment of phosphine, with no measurable off-site gas migration at the distances and height monitored.

ii. Internal Concentration (Mean Bin Concentration)

Internal phosphine concentration within the bin followed a time profile in which the concentration increased over the first three days, reached a maximum, and subsequently declined by day 5. The average bin concentration is summarized in Table 1.

Table 1. Mean phosphine concentration in the grain bin over 5 days of fumigation

Time after application (day)	Time (h)	Mean bin concentration (ppm)
0	0	0
1	24	210
2	48	353
3	72	400
4	96	300
5	120	180

Phosphine levels were near zero immediately after sealing, rose to an average of 210 ppm after 24 h, and approached a peak of an average of 400 ppm by day 3, before decreasing to 300 ppm at day 4 and 180 ppm at day 5.

iii. Vertical Distribution at Three Cable Heights

Phosphine concentrations at the three center-bin cable heights demonstrated consistent vertical stratification. The top cable (near the grain surface/headspace region) showed the highest concentrations, the middle cable was close to the bin mean, and the bottom cable (near the bin floor) had the lowest concentrations throughout the 5-day period. Table 2 presents the values used in the report.

Table 2. Phosphine concentrations at three cable heights and mean bin value over 5 days

Day	Time (h)	Top cable (ppm)	Middle cable (ppm)	Bottom cable (ppm)	Mean bin concentration (ppm)
1	24	330	220	80	210
2	48	480	400	180	353
3	72	500	430	270	400
4	96	380	320	200	300
5	120	230	180	130	180

These data showed that the maximum concentration reading was 500 ppm at the top cable by day 3, with the top cable consistently reading higher values and the bottom cable reading lower values relative to the bin average. By day 5, concentrations at all three positions declined in parallel with the mean bin concentration.

Although internal concentrations reached several hundred ppm during the fumigation, all external readings remained at 0 ppm throughout the sampling period. This contrast between internal and external measurements demonstrated that the bin sealing and structural integrity were sufficient to prevent detectable phosphine emissions at 1–2 m from the wall at 5 ft height under the conditions of the trial.

The trial showed that the SCAFCO grain bin, fumigated with Degesch Phostoxin pouches at the selected rate, provided high internal phosphine concentrations while preventing measurable

emissions at the monitored external locations. The 5-day concentration profile inside the bin featured a rise to peak levels of about 400 ppm on average followed by a decline to 180 ppm, consistent with effective fumigation exposure. Vertical concentration data from the three center-bin cables confirmed modest stratification, with higher phosphine levels near the grain surface and lower levels near the bin floor, while still reaching concentrations suitable for insect control across the grain mass.

Figures

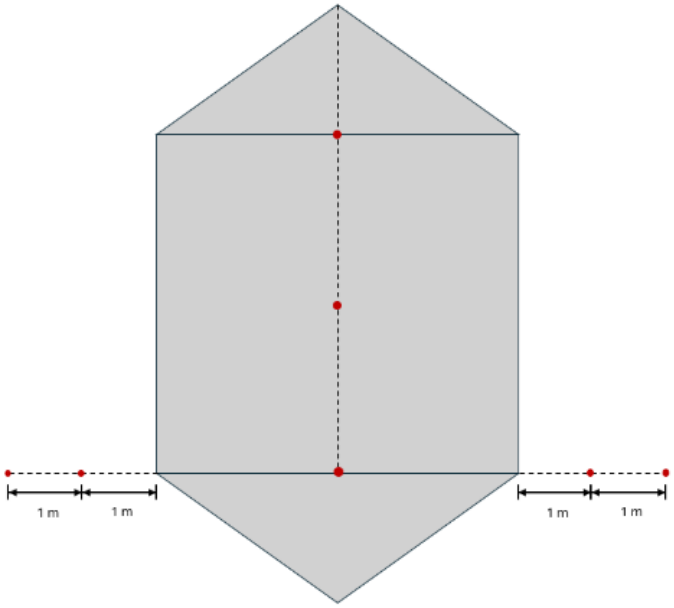

Figure 1. Layout of internal measuring points.

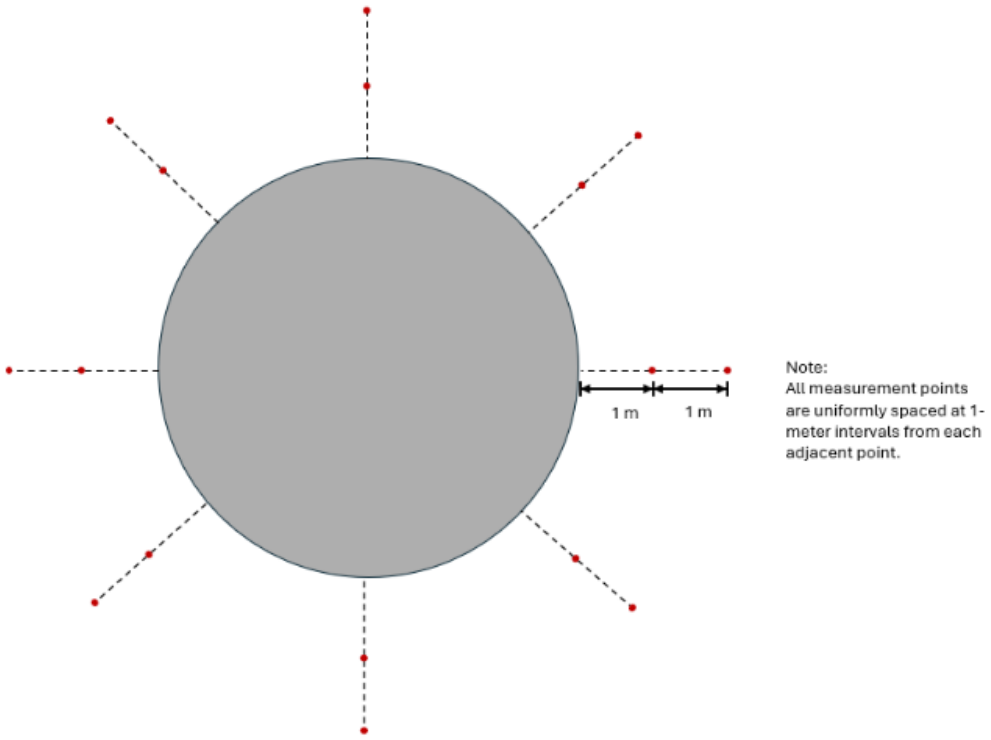

Figure 2. Layout of external measuring points.

Figure 3. Cables inside the bin.

Figure 4. Loading of wheat into the bin.

Figure 5. Fumigation from the top of the bin.

Conclusions:

Across the 5-day fumigation period, phosphine concentrations at all 16 external monitoring points remained below the instrument detection limit (0 ppm recorded at all readings). This outcome indicated that the bin maintained effective containment of phosphine, with no measurable off-site gas migration at the distances and height monitored.

PHOSPHINE GRAIN FUMIGATION EMISSION ESTIMATES BACKGROUND

PREPARED FOR THE NATIONAL GRAIN AND FEED ASSOCIATION

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1 OVERVIEW

The mass of phosphine in the fumigated container equals the initial mass of phosphine at the beginning of fumigation minus the mass of phosphine reacted and the mass of phosphine that flowed out of the container prior to ventilation due to leaks. The change in mass over time equation can be represented as:

Equation 1: $$\frac{dm}{dt} = \dot{m}_d - \dot{m}_l$$

Where:

dm/dt = change in phosphine mass in the container over time
$\dot{m}_d$ = rate of phosphine degradation
$\dot{m}_l$ = rate of phosphine leaking out of the container prior to ventilation

2 RATE OF PHOSPHINE DEGRADATION

The change in concentration of phosphine due to reaction is based on the second order half-life decay rate equation[1]:

Equation 2: $$\dot{c}_d = -k[C_t]^2$$

Where:

$\dot{c}_d$ = rate of phosphine molar concentration change due to phosphine degradation
C_t = molar concentration of phosphine in container at time t
k = phosphine degradation rate constant

The rate of phosphine molar concentration change due to phosphine degradation can be equated to the rate of phosphine mass change due to phosphine degradation ($\dot{m}_d$) as follows:

Equation 3: $$\dot{c}_d = \frac{\dot{m}_d}{V\ MW}$$

Where:

MW = molecular weight of phosphine, 33.99 mass per mass-mole
V = volume of container

The molar concentration of phosphine in the container at time t can be equated to the mass of phosphine in the bin at time t (M_t).

Equation 4: $$[C_t] = \frac{M_t}{V\ MW}$$

Where:

M_t = mass of phosphine in the bin at time t

Substituting Equations 3 and 4 into Equation 2 yields:

Equation 5: $$\frac{\dot{m}_d}{V\ MW} = k\left(\frac{M_t}{V\ MW}\right)^2$$

Simplifying Equation 5 yields:

Equation 6: $$\dot{m}_d = \frac{k}{V\ MW} M_t^2$$

The rate constant k is based on the half-life value of phosphine, which is 28 hours (t_h), and can be solved from the following second order half-life formula[2]:

Equation 7: $$t_h = \frac{1}{k[C_0]}$$

Where:

C_0 = initial molar concentration of phosphine in container at time t = 0

t_h = phosphine half-life or 28 hours in a dark environment (i.e., it is shorter when exposed to light)[3]

Solving for the rate constant k yields;

Equation 8: $$k = \frac{1}{t_h[C_0]}$$

The initial molar concentration of phosphine in the container at time 0 can be equated to the initial mass of phosphine in the bin at time 0 (M_0).

Equation 9: $$[C_0] = \frac{M_0}{V\ MW}$$

Where:

M_0 = initial mass of phosphine in bin at beginning of fumigation

Substituting Equation 9 into equation 8 yields:

Equation 10: $$k = \frac{1}{t_h\left(\frac{M_0}{V\ MW}\right)}$$

Simplifying Equation 10 yields:

Equation 11: $$k = \frac{V\ MW}{t_h M_0}$$

Substituting Equation 11 into equation 6 yields:

Equation 12: $$\dot{m}_d = -\frac{\left(\frac{V\ MW}{t_h M_0}\right)}{V\ MW} M_t^2$$

Simplifying Equation 12 yields:

Equation 13: $$\dot{m}_d = -\frac{M_t^2}{t_h M_0}$$

3 RATE OF PHOSPHINE LEAKING OUT OF THE CONTAINER PRIOR TO VENTILATION

The change in phosphine concentration due to phosphine leaking out of the container, is estimated to be negligible based on a Kansas State University study dated November 16, 2025[4]. Therefore, the leak rate was set to zero.

Equation 14: $$\dot{m}_l \approx 0$$

4 CHANGE IN PHOSPHINE MASS IN THE CONTAINER OVER TIME

Inserting equations 13 and 14 into equation 1 yields:

Equation 15: $$\frac{dm}{dt} = -\frac{M_t^2}{t_h M_0} - 0$$

Solving this formula for the mass change of phosphine in the container over time t yields:

Equation 16: $$-\frac{t_h M_0\, dm}{M_t^2} = dt$$

To determine the mass of phosphine in the container over time, we integrate this equation from the start of the fumigation, where t equals zero and the mass of phosphine equals M_0, to just before the container is ventilated, time t, which yields:

Equation 17: $$\int_{M_0}^{M_t} -\frac{t_h M_0}{M_t^2}\, dm = \int_0^t dt$$

Solving the integral on the left side of equation 16 (i.e., the mass integral) results in the following formula:

Equation 18:

$$\frac{t_h M_0}{M_t} - \frac{t_h M_0}{M_o} = t - 0$$

Simplifying and rearranging equation 18 (i.e., the mass integral) so you can solve for M_t

Equation 19:

$$\frac{t_h M_0}{M_t} - \frac{t_h M_0}{M_o} = t - 0 = \frac{t_h M_0}{M_t} - t_h = t \rightarrow \frac{t_h M_0}{M_t} = t + t_h \rightarrow M_t = \frac{t_h M_0}{t + t_h}$$

5 TOTAL PHOSPHINE EMISSIONS

The total phosphine emissions M_{total} are the quantity of phosphine remaining in the container at the end of fumigation (M_t) which will be ventilated, and the phosphine that leaked out during fumigation (M_l) which was assumed to be negligible.

Equation 20: $$M_{total} = M_t + M_l = M_t$$

Substituting equation 19 into equation 20 yields:

Equation 21: $$M_{total} = \frac{t_h M_0}{t + t_h}$$

The initial mass of phosphine in a bin (i.e., the initial mass generated) can be represented by the following equation:

Equation 22: $$M_0 = F * PG$$

Where:

F = Quantity of Fumigant Used (Number of Cylinders, Pellets, Plates, Strips or Tablets)
PG = phosphine generated per fumigant type in pounds from Column G

Substituting equation 22 into equation 21 and replace t_h with 28 hours yields:

Equation 23: $$M_{total} = \frac{28 * F * PG}{t + 28}$$

Where:

F = Quantity of Fumigant Used (Number of Cylinders, Pellets, Plates, Strips or Tablets)
M_{total} = Phosphine emissions in pounds
PG = phosphine generated per fumigant type in pounds
t = Fumigation time in hours

6 ASSUMPTIONS

6.1 Fumigant Generation Rate

At the start of fumigation (t = 0), the phosphine is assumed to be completely generated and uniform throughout the container. When solid phosphides are used to generate the phosphine, they are not expected to evolve phosphine immediately. Additionally, the distribution of phosphine will likely not be uniform initially until it has time to diffuse. If the phosphine concentrations were higher relative to a leak, the leak rate would be expected to be higher.

6.2 Leak Flow Rate Is Negligible

As mentioned earlier, the leak flow rate is assumed to be negligible relative to the overall emissions occurring at the end of the fumigation.

6.3 Reaction Kinetics

Limited data was identified on the phosphine degradation reaction kinetics. The reaction was assumed to be a second order reaction based on the reaction rate constant, but it is not known if the phosphine, or other reactants, such as a hydroxyl radical, are rate limiting.

7 REFERENCES

[1] The reaction is assumed to be a second order reaction based on the rate constant units (cubic centimeters per second) provided in "Fate of Phosphine in the Atmosphere" by Dr. R. Frank and Dr. G Rippen, Battelle-Institut e.V., Franfurt am Main, January 1987, page 6.

[2] Chemistry LibreTexts™ Second-Order Reactions website last updated June 5, 2019 https://chem.libretexts.org/Bookshelves/Physical_and_Theoretical_Chemistry_Textbook_Maps/Supplemental_Modules_(Physical_and_Theoretical_Chemistry)/Kinetics/Reaction_Rates/Second-Order_Reactions.

[3] "R.E.D. Facts Aluminum and Magnesium Phosphides" United States Environmental Protection Agency, Prevention, Pesticides and Toxic Substances, December, 1998, Page 5.

[4] "Estimating Phosphine Emissions During Grain Bin Fumigations" by Kaliramesh Siliveru, Ph.D. Kansas State University, Manhattan, Kansas, November 16, 2025, page 8.

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1 General

To treat or deter insect infestation, companies may fumigate their grain and feed commodities with one of various grain fumigants including several fumigants that use phosphine gas, which is a hazardous air pollutant (HAP)[1]. The following information provides an overview of the fumigation process and provides methods for calculating the phosphine emissions.

2 Process Description

2.1 Introduction

Phosphine gas and phosphine generating materials are restricted use pesticides. Under the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA), restricted use pesticide applicators are required to follow the label instructions (i.e., it is a federally enforceable requirement)[2]. These label instructions typically require:

- Oversight by a certified/trained applicator,
- Preparation of a fumigation management plan,
- Maximum allowable fumigation dosages,
- Sealing the fumigated container to prevent leaks and maintain fumigant concentration in the container,
- Monitoring and correcting leaks, if identified[3].

Because the label instructions are federally enforceable requirements, they are appropriately considered when calculating the potential-to-emit.

The following sections provide a description of the fumigation process.

2.2 Container Sealing

The first fumigation step is to seal the grain or feed commodity storage container. Although this is typically a grain bin, it can also be a transport container such as a railcar, tractor trailer or intermodal container or a pile of grain covered with a tarp. Sealing the container assures that an adequate phosphine concentration is maintained during fumigation process[4]. Sealing also limits potential human exposure to the phosphine. The label instructions prohibit fumigating containers that cannot be adequately sealed[5]. Additionally, if the applicator detects a leak that could expose workers or bystanders to concentrations above 0.3 parts per million (ppm), the applicator must attempt to seal the leak[6].

2.3 Fumigation

After sealing the container, the fumigant is introduced into the container. The amount of fumigant used is based on the commodity type, size of the bin and degree of infestation[7]. At lower temperature, insect control is more difficult, and the phosphine generating materials (e.g., pellets, tablets, plates and strips) generate phosphine slower. Therefore, the retention time is longer at lower temperatures and prohibited

below certain temperatures (e.g., 40 degrees Fahrenheit for some phosphine generating materials)[8]. Table **2.3-1** provides an example of the exposure period required for various temperatures.**Table 2.3-1**

Table 2.3-1: Typical Minimum Exposure Periods for Phosphine Fumigants[9]

Temperature	Pellet	Tablet
40°F or less	Do not fumigate	
41°F to 53°F	8 days	10 days
54°F to 59°	4 days	5 days
60°F to 68°F	3 days	4 days
Above 68°F	2 days	3 days

°F = Degrees Fahrenheit

Since insects are inactive at temperatures below 43 degrees Fahrenheit, fumigation is not necessary[10].

Phosphine fumigation is typically conducted using either compressed phosphine gas stored in a cylinder or using phosphine generating materials that react with moisture in the air to form phosphine gas. When compressed phosphine gas is used for the application, it is metered into the container from cylinders until the desired quantity is applied.

When phosphine generating materials are used, they are removed from their gas-tight containers and placed in various locations in the container and allowed to react with moisture in the air. Phosphine generating materials are stored in gas-tight containers to prevent inadvertent reactions, so emissions are not expected in storage prior to fumigation.

The fumigated container is kept sealed for the designated exposure period, which varies depending upon the temperature of the fumigated material (i.e., longer time periods in colder temperatures)[11].

2.4 Ventilation

At the end of the fumigation timeframe, the applicator ventilates the fumigated container, so any remaining phosphine is expected to be emitted during this phase. The ventilation continues until the phosphine concentration is 0.3 ppm or less (i.e., the threshold limit value for phosphine)[12].

3 Emissions and Controls

3.1 Phosphine Generation

The quantity of phosphine generated during fumigation varies depending upon the fumigant chemicals used to generate the phosphine. When phosphine generating materials are used, the quantity of phosphine generated varies depending upon the chemical used Table 3.1-1 identifies the various chemical reactions and associated quantity of phosphine generated per quantity of the chemical used.

Table 3.1-1: Fumigant Chemical Reactions

Chemical	Chemical Molecular Weight[13]	Chemical Reaction[14]	Moles Fumigant Generated Per Mole Chemical	Molecular Weight Fumigant	Phosphine Generated by Chemical
	(lb chemical/ lbmole chemical)		(lbmole fumigant/ lbmole chemical)	(lb fumigant/ lbmole fumigant)	(lb fumigant/ lb chemical)
A	B	C	D	E	G=E/B*D
Aluminum Phosphide	57.96	$AlP+3H_2O \Rightarrow Al(OH)_3+PH_3$	1	34.0	0.59
Magnesium Phosphide	134.9	$Mg_3P_2+6H_2O \Rightarrow 3Mg(OH)_3+2PH_3$	2	34.0	0.50
Phosphine		No reaction	1	34.0	1
Zinc Phosphide	258.1	$Zn_3P_2+6H_2O \Rightarrow 3Zn(OH)_3+2PH_3$	2	34.0	0.26

lb = pounds, lbmoles – pound moles

The concentration of phosphine or phosphine generating chemical in a fumigant vary between commercial products. Table 3.1-2 provides the pounds of phosphine generated by a fumigant for various commercial phosphine fumigants. This list of fumigants does not imply endorsement by Bunge.

Table 3.1-2: Pounds of Phosphine Generated Per Fumigant

Fumigant	Active Ingredient[15]	Maximum Concentration[16]	Phosphine Generated by Active Ingredient	Fumigant Type	Fumigant Weight	Phosphine Generated
		(%)	(lbs phosphine/lb active ingredient)		(lbs)	(lbs/ fumigant)
A	B	C	D	E	F	G=C*D*F
$Eco_2Fume^{®}$	Phosphine	2%	1.00	Cylinder	68.34	1.5
Fumi-Cell®	Magnesium Phosphide	56%	0.50	Plate	0.26	0.073
Fumi-Cell®	Magnesium Phosphide	56%	0.50	Strip	5.15	1.5
Magnaphos®	Magnesium Phosphide	56%	0.50	Plate	0.26	0.074
Magnaphos®	Magnesium Phosphide	56%	0.50	Strip	2.63	0.74
Phostoxin®	Aluminum Phosphide	55%	0.59	Pellet	0.00132	0.00043
Phostoxin®	Aluminum Phosphide	55%	0.59	Tablet	0.00661	0.0021
$VaporPh_3os^{TM}$	Phosphine	100%	1.00	Cylinder	48.5	48.5

lb = pounds, % = percent

3.2 Phosphine Degradation

The calculations shown in Table 3.1-2 are the quantity of phosphine generated in the fumigated container and do not account for degradation of product prior to emission to the environment. Phosphine reacts with constituents in the air and therefore has a short life in the lower atmosphere[17]. Although the exact reaction mechanism may vary, phosphine degrades through reactions with oxygen and/or hydroxyl radicals in air and eventually forms inorganic phosphates such as phosphoric acid[18 and 19]. These end products are not HAPs, volatile organic compounds (VOC) or criteria pollutants. These inorganic phosphates end up as residues on the grain[20].

Table 3.2-1 shows data on the concentration reduction over time during grain fumigation (i.e., the concentration of phosphine in the bin) and demonstrates the phosphine reactivity inside the fumigation container.

Table 3.2-1: Phosphine Reduction During Fumigation[21]

Bin	Initial Concentration	Time Allotted	Final Concentration	Percent Reduction
	ppm	hr	ppm	%
114	999	72	2.69	99.73%
114	999	96	2.21	99.78%
114	999	120	2.29	99.77%
117	999	72	0.75	99.92%
117	999	96	0.77	99.92%
117	999	120	0.81	99.92%
House 3	999	96	0.62	99.94%
House 3	999	144	1.56	99.84%

ppm = part per million, initial concentration was 0.04 grams phosphine per cubic foot, which is equivalent to 1,000 ppm.

Although a total of 523 samples were associated with this data, 415 were below the 0.1 ppm threshold and 53 were between 0.1 and 0.5 ppm. Only 55 samples between 0.5 and 10 ppm were used for this table[22]. Therefore, this data provides a conservative representation of the phosphine degradation.

3.3 Container Leaks

Although most (i.e., over 99%) of the phosphine appears to degrade prior to ventilating the storage container, some of the phosphine may leak out prior to degradation even though the fumigant label requires sealing of the container.

A study by Kansas State University showed no detectable leaks of phosphine during fumigation[23]. This study was conducted on steel grain bins, which would be considered less impervious than concrete bins and ground storage piles.

3.4 Phosphine Emissions

The formula for the quantity of phosphine emitted is[24]:

$$PE = \frac{28 * F * PG}{28 + t}$$

Where:

F = Quantity of Fumigant Used (Number of Cylinders, Pellets, Plates, Strips or Tablets)

PE = Phosphine emissions in pounds

PG = phosphine generated per fumigant type in pounds from Table 3.1-2, Column G

T = Fumigation time in hours

4 References

[1] Clean Air Act, Title I – Air Pollution Prevention and Control, Part A – Air Quality and Emission Limitations, Section 112 Hazardous Air Pollutants, Petitions Process, Lesser Quantity Designations, Source Category List, As Amended Through P.L. 108-201, February 24, 2004.

[2] 40 Code of Federal Regulations part 156.10(i)(2)(ii).

[3] "Applicator's Manual PH3 Aluminum Phosphide Fumigant Pellets/Tablets", Douglas Products and Packaging Company, Liberty, Missouri, June 2011, Pages 6 through 14.

[4] "Degesch Phostoxin® Tables and Pellets label, D & D Holdings, Inc., Weyers Cave, VA, April 2016, page 14 to 20.

[5] "Applicator's Manual PH3 Aluminum Phosphide Fumigant Pellets/Tablets", Douglas Products and Packaging Company, Liberty, Missouri, June 2011, Page 14

[6] "Degesch Phostoxin® Tables and Pellets label, D & D Holdings, Inc., Weyers Cave, VA, April 2016, page 15.

[7] "Applicator's Manual For Aluminum Phosphide Fumigant Tablets, Pellets and Gas Bags", United Phosphorus, Inc., King of Prussia, Pennsylvania, April 2010 page 8.

[8] "Degesch Phostoxin® Tables and Pellets label, D & D Holdings, Inc., Weyers Cave, VA, April 2016, page 15.

[9] "Degesch Phostoxin® Tables and Pellets label, D & D Holdings, Inc., Weyers Cave, VA, April 2016, page 8.

[10] "Insects Infesting Stored Grain and Seeds" by Harold H. Shepard, University of Minnesota Agricultural Experiment Station Bulletin 340, Reprinted June 1947, Page 24.

[11] "Applicator's Manual 04112017-6782 UPI Magnesium Phosphide Fumigant Magnaphos Plate" United Phosphorus, Inc., King of Prussia, Pennsylvania, October 2016, Page 5

[12] "Degesch Phostoxin® Tables and Pellets label, D & D Holdings, Inc., Weyers Cave, VA, April 2016, page 15.

[13] "Use Information and Air Monitoring Recommendations for the Pesticide Active Ingredient Phosphine" by the State of California Environmental Protection Agency Department of Pesticide Regulation, September 2008, page 4 lists the active ingredients.

[14] "Use Information and Air Monitoring Recommendations for the Pesticide Active Ingredient Phosphine" by the State of California Environmental Protection Agency Department of Pesticide Regulation, September

2008, page 8. Based on reactions identified in this document with the exception of Zinc Phosphide which was estimated based on the chemical formula.

[15] "Use Information and Air Monitoring Recommendations for the Pesticide Active Ingredient Phosphine" by the State of California Environmental Protection Agency Department of Pesticide Regulation, September 2008. The active ingredient list was limited to those that emit phosphine

[16] Based on information from product safety data sheet or pesticide label, where available

[17] "Fate of Phosphine in the Atmosphere" by Dr. R. Frank and Dr. G Rippen, Battelle-Institut e.V., Franfurt am Main, January 1987, page 7

[18] "The Fate of Phosphine in the Atmosphere" by Dr. Ekkehard Fluck, Institut für Anorganische Chemi der Universität Stuttgart, Stuttgart, West Germany, February 1973, pages 3 to 6.

[19] "Fate of Phosphine in the Atmosphere" by Dr. R. Frank and Dr. G Rippen, Battelle-Institut e.V., Franfurt am Main, January 1987, page 7

[20] "Phosphorus Residues in Wheat Due to Phosphine Fumigation" by R. TKACH UK, Board of Grain Commissioners, Grain Research Laboratory, Winnipeg 2, Manitoba and American Association of Cereal Chemists, Inc., St. Paul, Minnesota, 1972, page 260

[21] "Analysis of Phosphine Concentrations from Fumigation Sites" by Victor M. Canez, PhD, the Acta Group, Washington, D.C., February 25, 2016, Table 7, page 19.

[22] "Analysis of Phosphine Concentrations from Fumigation Sites" by Victor M. Canez, PhD, the Acta Group, Washington, D.C., February 25, 2016, Table 7, page 19.

[23]"Estimating Phosphine Emissions During Grain Bin Fumigations" by Kaliramesh Siliveru, Ph.D. Kansas State University, Manhattan, Kansas, November 16, 2025, page 8.

[24] "Phosphine Grain Fumigation Emission Estimates Background" by the National Grain and Feed Association, Arlington, Virginia, January 15, 2026