Cooperative Research Centre
for National Plant Biosecurity

Final Report

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Technology to overcome inadequate fumigations and resistance selection

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1. Executive summary

This project aimed at quantifying the efficacy of fumigant doses as applied in Australia; and for phosphine, how different doses may select for resistance. It encompassed modelling the interrelated factors affecting fumigant doses within fan-forced fumigated grain stores (mortality, distribution, sorption, leakage) and analysed performance under various practical scenarios. This project has quantified each of the phenomena involved in applying fumigants in industrial grain stores and demonstrated the significance of each via field trials and mathematical modelling. Efficacy, sorption, and flow dispersion influences were defined with extensive sets of laboratory experiments.

The laboratory effort achieved an extensive data set quantifying phosphine, methyl bromide and ethyl formate sorption by grain and the role of key factors grain type, temperature, moisture and field batch. A mathematical model defining the kinetics of this sorption was developed and applied to predict concentrations and grain residues for practical fumigation scenarios. A data set defining the intergranular gas flow dispersion coefficients of packed beds of grain was obtained and implemented with the sorption kinetics data in a mathematical model to address the 'spreading and diluting' of sorptive fumigants as they are pumped through three dimensional grain stacks, with ethyl formate based fumigations. This modelling and experimental effort demonstrated that these phenomena are the most significant issues for modern fumigants based on ethyl formate (EF), and the use of EF based fumigants can be successful if system designs account for their effect.

This project quantified the effect of daily interrupted phosphine doses on representative insects to define the role of store gas-tightness in disinfestation performance. Efficacy models, including interrupted doses and different resistance levels, were used to determine that interruptions during an exposure of PH_3 do not cause deficient fumigations if an adequate overall accumulated exposure is achieved. This is usually the case in reasonable practical fumigations, which means that considerable lenience in store gas-tightness can be afforded for effective disinfestation, contrary to advise currently promoted to industry. Also, fumigations failures and possible resistance selection is unlikely with phosphide tablet reaction based dispensing where continual 'topping up' occurs, but the growing trend of 'instant release' technologies (generators, Eco$_2$Fume) can incur these risks. Lastly, a series of field trials that defined the performance of an integrated fan-forced PH_3 fumigation and aeration-cooling system were completed, demonstrating strong disinfestation and repeat fumigation prevention characteristics of this combination. The dominant role of sorption and 'silo breathing' in gastight stores was demonstrated.

2. Aims and objectives

In Australia, fumigation is the mainstay for stored grain pest control with over 80% of Australia's grain fumigated with phosphine, which is under threat due to increased resistance and OHS&E concerns. The main cause of resistance development in industry is repeated application of deficient fumigations where doses are insufficient in either concentration or exposure period, or both. There are several causes of these deficiencies in practice: inadequate distribution of fumigant throughout grain stores; a high proportion of "leaky" stores that cannot maintain phosphine doses; and procedures that prematurely stop fumigations before disinfestation is complete. These practices result from inadequate information of how fumigants distribute in, or are lost from, industrial stores, along with commercial pressures that require rapid grain disinfestation and restrict investment in the fumigation capability of stores. These commercial pressures are so dominant across the modern Australian industry, that innovative phosphine application methods that overcome deficiencies and avoid repeating phosphine fumigations are required.

This project aimed at quantifying the efficacy of fumigant doses as applied in Australia, including how different doses select for resistance. It encompasses modelling the interrelated factors affecting fumigant doses within a store (mortality, distribution, sorption, leakage) and analysing performance under various practical scenarios (e.g. imperfect stores, different weather events, different operational scenarios). Using this modelling, innovations with application methods for phosphine and prospective alternative fumigants will be developed. The innovations are based on timing the application of phosphine doses, fan-forced distribution of fumigants, integrating fumigation with grain temperature control (aeration-cooling). For this project, the innovations focused on large silos which are commonly used by growers and bulk handling companies.

The specific outcome related objectives of this project were to develop:

- innovative fumigation strategies based on application timing and fan-forced distribution that cost-effectively overcome the main causes of deficient fumigation, imperfect stores amid typical weather events, to sustain the useful life of phosphine and enable the effective application of new fumigants
- an integrated aeration-fumigation technology for faster, more reliable and sustainable grain disinfestation while providing an option that minimises selection of insects resistant to phosphine by reducing population growth rates and repeat fumigations

3. Key findings

3.1 Mortality of ‘interrupted’ phosphine exposures, common to industry

In summary, this project quantified the effect of diurnally interrupted doses of phosphine on the representative insect Sitophilus oryzae (L.) eggs and determined that interruptions during an exposure of PH_3, do not cause deficient fumigations if an adequate overall accumulated exposure is achieved. This is usually the case in reasonable practical fumigations, which means that considerable lenience in store gas-tightness can be afforded for effective disinfestation.

The majority of published insect mortality responses to phosphine have been measured using continuous exposures at constant concentrations. However, phosphine concentrations in industrial grain stacks can vary substantially. Phosphine displacement and dilution caused by wind; and air exchange into and out of a store due to its expansion and contraction with temperature changes (silo ‘‘breathing’’) are ever-present major influences. Diurnal changes in solar heat exchange, ambient air temperatures and wind velocity drive these naturally occurring processes. The nature of these varying concentrations is influenced by the type of storage and the degree to which it is gas-tight. In Australia it is estimated that the majority of grain is fumigated in stores that do not meet reliable gas tightness standards. Also, fumigators determine if a fumigation is adequate based on PH_3 concentration measurements, as insect measurement is inexact and comparatively expensive. While higher performing fumigation systems involving fan-forced phosphine reticulation can distribute this fumigant throughout a grain stack quite effectively and reduce zones of inadequate concentrations, especially in large stores, weather induced dilution near store boundaries is very difficult to prevent and may still stop lethal concentrations being achieved. It was recognized that in practice, provided a store exhibited basic gas-tightness (e.g. no open eaves); these diluted zones exhibited a diurnal cycle and 'recovered' for significant periods of the day. So from a disinfestation perspective, how long can a "diurnal interruption" to a PH_3 exposure exist before disinfestation failures are incurred?

This project investigated this question with a specific set of bioassays focused on insect mortality response to repeated sub-lethal doses of phosphine. The treatments used were designed to approximate phosphine exposures undergoing simple diurnal fluctuations. Eggs of a *Sitophilus spp* were selected for examination as they represent a phosphine tolerant development stage of a tolerant stored-grain insect genus. In this project, three strains of the species *Sitophilus oryzae* (L.) with varying phosphine tolerance were used, because it is an abundant species in Australia, whose population growth rates are well defined for future modeling of the data. The effect of phosphine on egg mortality was assessed using two treatment regimes; one was diurnally interrupted, the other continuous. Both regimes were made comparable such that insect eggs were subjected to the same phosphine concentration for the same accumulated length of time. However, in the former regime, the treatment was 'interrupted' and the fumigant concentration administered as a consistent proportion of each day with an intervening phosphine-free period. Doses with these characteristics are typical of the critical zones within grain stores where gas movement, leakage, etc, cause suspected inadequate exposures. The data from the experiments completed in this project and relevant published data, have been used to predict disinfestation performance for insects exhibiting a range of PH_3 tolerances, including resistant strains, for PH_3 concentration profiles measured throughout the range of conditions measured in a series of field trials (described below in this report).

Figure 3.1.1 illustrates the characteristics of an interrupted PH_3 exposure as measured in a field trial of this project (described below). This trial involved a high quality gas-tight silo of 1500tonnes capacity, which was fumigated using a recirculated fan-forced PH_3 dispensing system. That is, this fumigation was completed using equipment considered as 'good as it gets'. A controlled leak was introduced into the silo at a lower sight-glass (1600mm above the ground) and instrumented with a series of sampling to lines to investigate the extent, timing and causes of these leaks (explained below). Figure 3.3.1 illustrates how PH_3 exposures are interrupted during a 24h daily cycle up to 500mm into the grain from the silo wall, despite the PH_3 being pumped past this leak by an electrically powered fan.

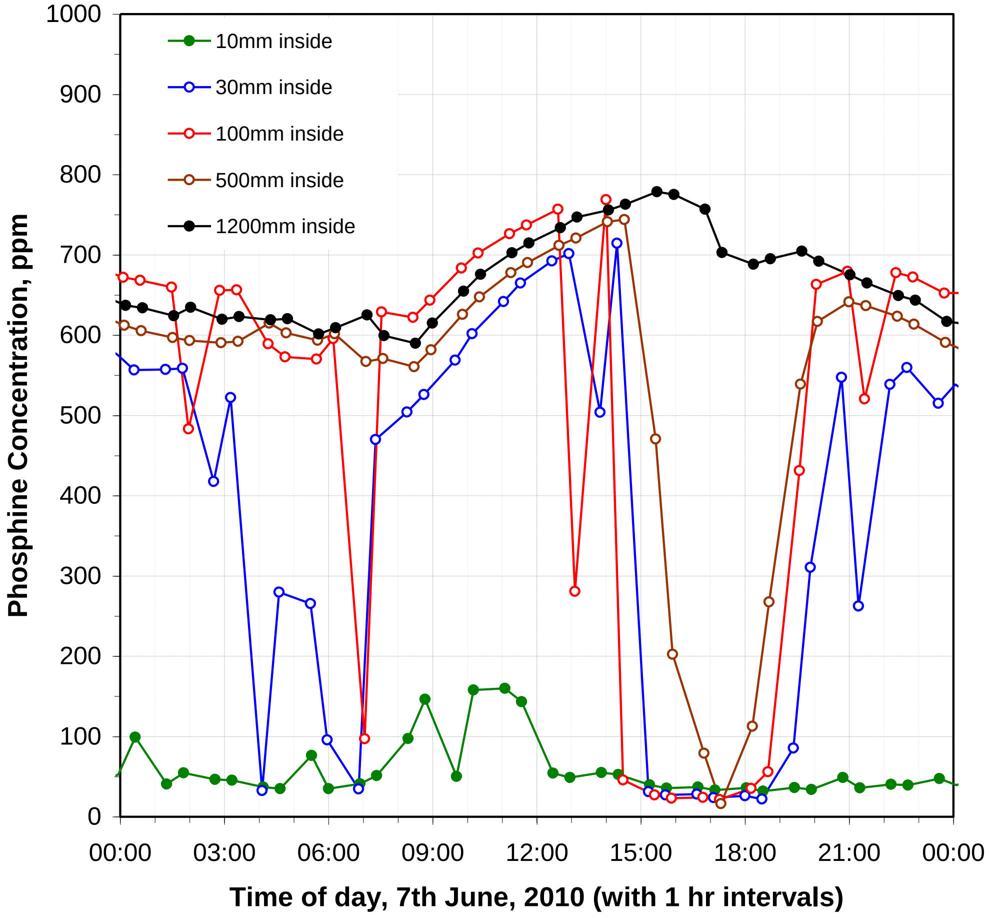

Figure 3.1.1. Concentrations of phosphine in air samples withdrawn from 10, 30, 100, 500 and 1200 mm into the grain mass perpendicular to a "controlled leak" (modified sight-glass) of a 1500 tonne trial silo.

Figure 3.1.2 illustrates the mortality characteristics of daily interrupted PH_3 exposures in comparison to continuous PH_3 exposures across a total four day period. Figure 3.3.2 shows that complete mortality was achieved by the interrupted exposures, at a slower rate. The interrupted exposures were substantially reduced doses of 4.2% (4hr/day) and 8.3% (8hr/day) of the continuous exposures. Quite significantly, a dose that exposes one of the hardest to kill grain pests (eggs of *S. oryzae*) for only four hours per day to $300ppm_v$ was efficacious, which shows that large daily interruptions during an exposure of PH_3 did not cause a disinfestation failure with an overall four day accumulated exposure. This scenario is quite analogous to many practical PH_3 fumigations where wind and "silo breathing" does dilute localized zones of a grain stack to negligible concentrations, but night time periods see PH_3 concentrations recover in these zones, often to concentrations much higher than $300ppm_v$ (see Figure 3.1.1).

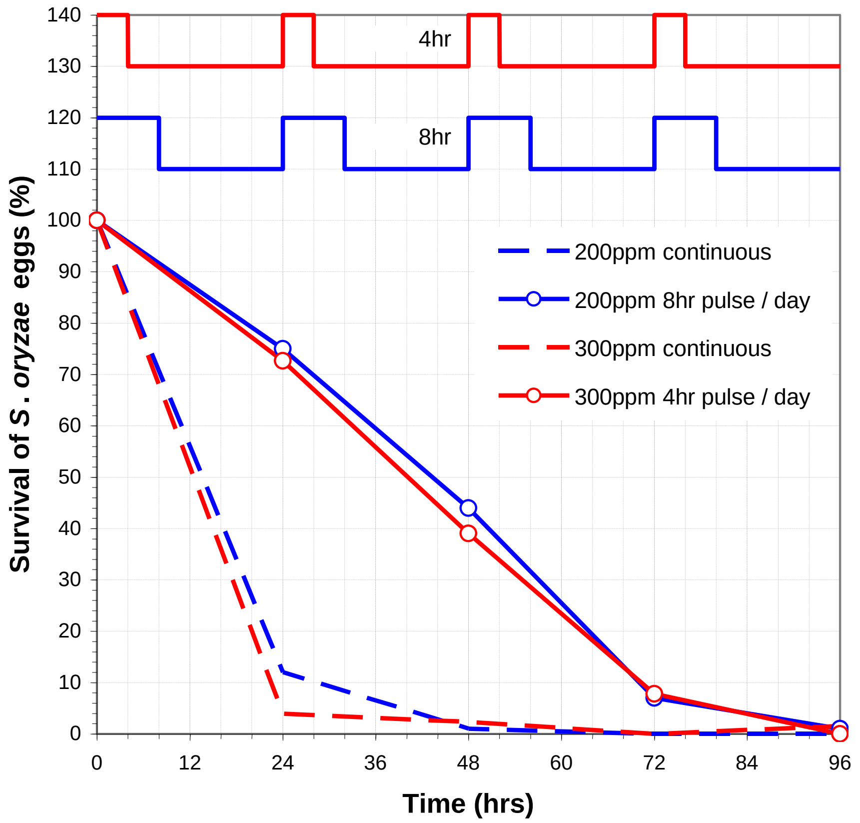

Figure 3.1.2. Comparison of the mortality response of *S. oryzae* (eggs) to interrupted (pulse) and continuous exposures of phosphine, over four days total time period. The two interrupted PH_3 exposures had similar order total 'c.t' products; $200ppm_v$ for eight hours per day (1600ppm.hr) and $300ppm_v$ for four hours per day (1200ppm.hr), whereas the continuous exposures were 12 and 24 greater doses respectively (19,200ppm.hr and 28,800ppm.hr).

Figure 3.1.3 summarizes all the measured mortality data comparing daily interrupted PH_3 exposures to continuous PH_3 exposures, but presents the data in terms of 'dosage period'. That is, the dosage period for daily interrupted exposures refers to the hours of PH_3 exposure only, and does not include the period of time where the insects were removed from the PH_3 exposure (which is included in the x-axis of Figure 3.1.2). Figure 3.1.3 illustrates the 'classical' dosage trade-off for a common mortality level (isobole), where decreasing concentrations require longer exposure periods for the same level of death. This is evident in both interrupted and continuous exposures. In particular, this Figure shows that interrupted exposures of PH_3 impart a stronger insecticidal affect than the equivalent 'c.t' product dose (exactly), for a common strain of *S. oryzae*. In fact, the dosage time is reduced somewhat by an apparent increase in phosphine toxicity when it is administered in stages. These trends were exhibited by susceptible and resistant strains of *S. oryzae*. This finding is industrially meaningful when making mortality predictions for practical (field trial or industry monitored) interrupted PH_3 exposures. For example, a 'c.t' product for a PH_3 concentration profile measured in an industrial grain store, can be based on an accumulated exposure period with removal of periods where PH3 concentrations was negligible, and the resultant mortality prediction will be conservative. A more accurate prediction (non conservative) can be made by establishing a new 'c.t' isobole for the interrupted dose.

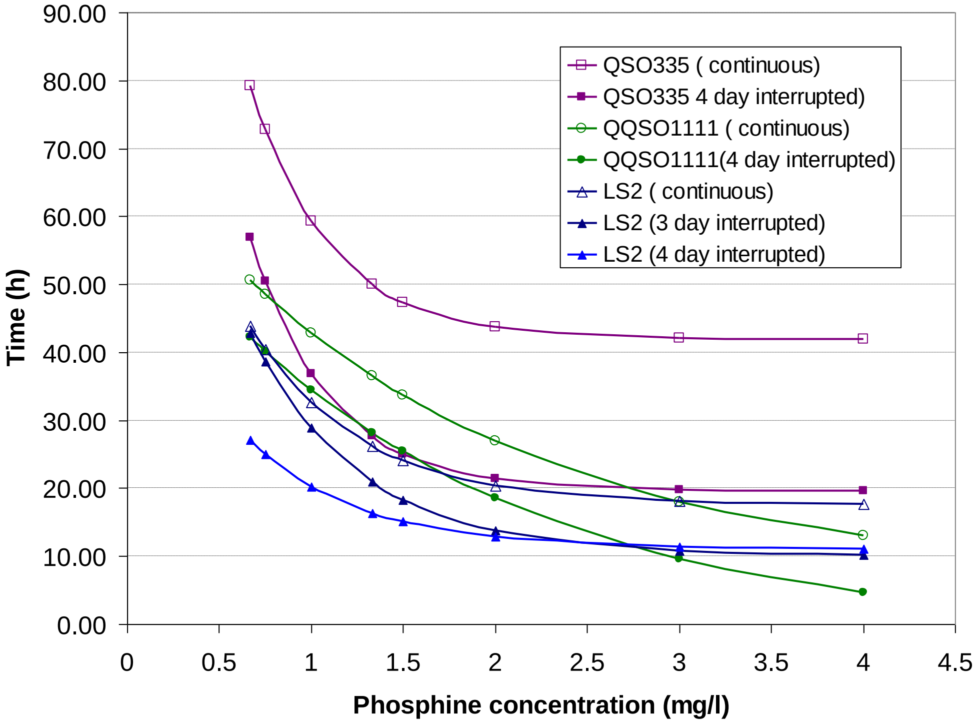

Figure 3.1.3. Dosage period to achieve $LT_{99.9}$ for three strains of S. oryzae eggs for continuous and interrupted exposures over four days. The dosage period for daily interrupted exposures refers to the hours of PH_3 exposure only. (For PH_3 $1mg.L^{-1}$ ~ $810ppm_v$)

3.2 Modelling the sorption of fumigants by grain

In summary, this component of this project quantified via data measurement and modelling the extent that fumigant sorption can cause deficient fumigations in industrial grain stores.

When a fumigant is present in air and comes into contact with grain, fumigant transfers from this dilute gaseous mixture to accumulate on the grain solid. This process is one form of adsorption, although the broader term 'sorption' is commonly used for grain–fumigant–air system. Fumigant sorption has been previously measured to be dependent on a variety of fumigant and grain factors including fumigant type, vapour concentration, exposure period, grain type, particular batch of grain, temperature and moisture. Each pairing of grain type with fumigant type exhibits its own characteristic sorption rate curve. Fumigant sorption becomes critical to fumigation performance when gaseous concentrations decrease below insecticidal levels before all insect pests are killed and when adsorption results in the grain acquiring chemical residue levels unacceptable to trade. Sorption involves various mass transfer, diffusion and reaction processes, which have not been quantified specifically. Predicting gaseous fumigant concentrations and grain residues during practical fumigations, which involves a large range of levels of the factors listed above, is most effectively tackled using a validated mathematical model of the sorption kinetics. This project developed such a model, compiled and analysed existing sorption data of CSIRO, and measured sorption data for new fumigants deemed important for industry (VaporMate, GL02, Eranol). A key aim was to develop a model that would account for all significant fumigant transport components while being able to be used in 3D computational fluid dynamics (CFD) models of fan-forced and natural convection based simulations of silo fumigations. The component efforts completed in this project are summarized as follows.

- The extensive CSIRO laboratory batch sorption data set for phosphine and methyl bromide was compiled and analysed.
- The sorption characteristics of 'new' ethyl formate based fumigants was measured, as well-mixed batch and 1D advective flow experimental efforts.
- A mathematical model of the sorption kinetics that could predict fumigant vapour and grain concentrations as a function of dose and basic grain physical chemistry parameters.

The most industrially relevant laboratory batch sorption experiment findings are presented in Figures 3.2.1, 3.2.2, 3.2.3, 3.2.4 and 3.2.5, where each Figure illustrates the influence of a key factor on the adsorption phenomena. These Figures show plots of raw data with fitted trend-lines. Figures 3.2.1, 3.2.2 and 3.2.3 show how oilseeds, the pulses fababeans and chickpeas, and the cereals oats and sorghum display relatively strong phosphine adsorption characteristics, such that even stores with fan-forced distribution systems are likely to incur zones where concentrations are inadequate due to adsorption losses. Significantly, the most common cereal wheat is the least sorptive grain type produced in Australia. Figure 3.2.4 illustrates how higher temperature 'trade dry' wheat (<12% moisture) will incur substantially greater sorption losses, while Figure 3.2.5 illustrates how the variation in sorption between field batches of a single wheat variety is high.

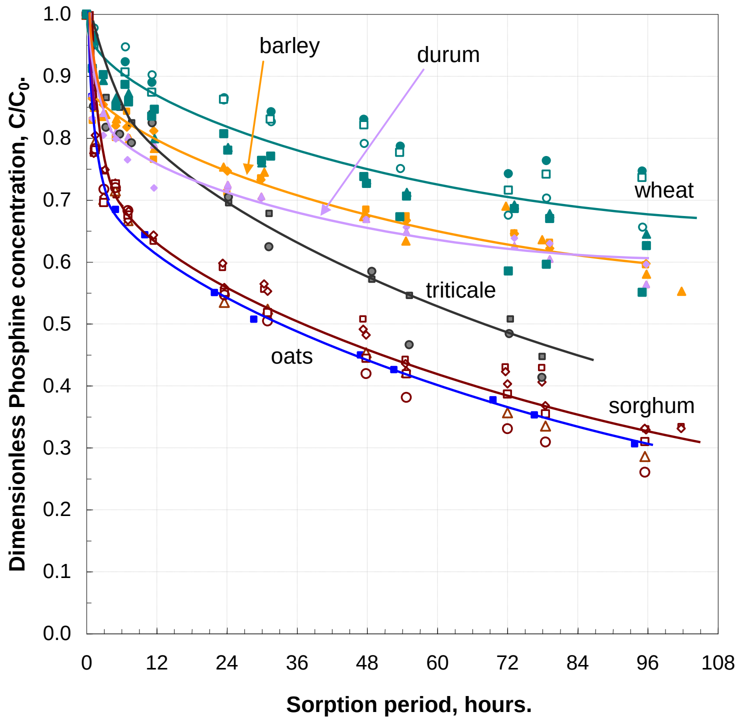

Figure 3.2.1. Illustration of the influence of grain type on batch phosphine adsorption for cereals (grain; 60% e.r.h., 25ºC, 95% filling ratio, initial concentration of 1g.m^{-3} as if flask was empty).

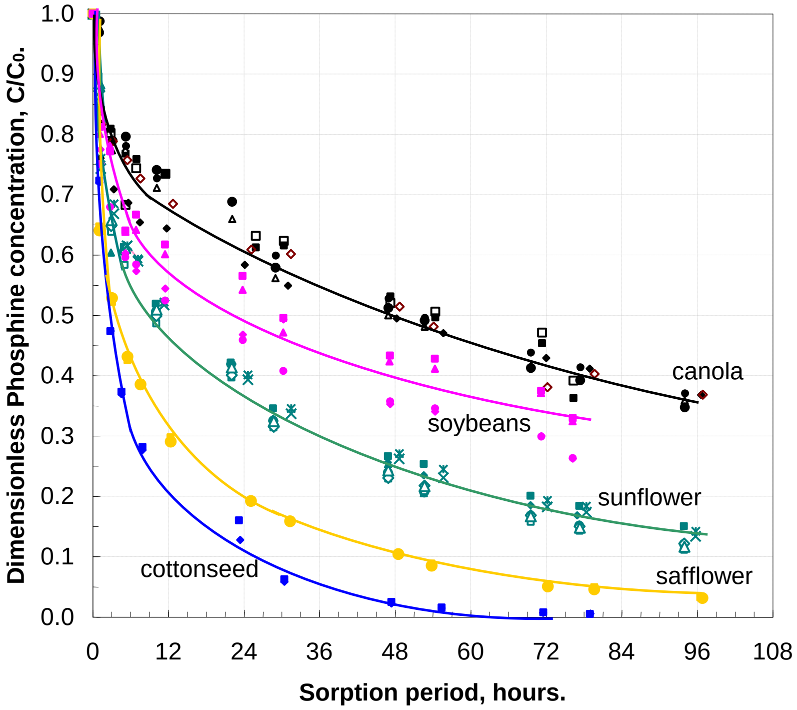

Figure 3.2.2. Illustration of the influence of grain type on batch phosphine adsorption for oilseeds (grain; 60% e.r.h., 25ºC, 95% filling ratio, initial concentration of 1g.m^{-3} as if flask was empty).

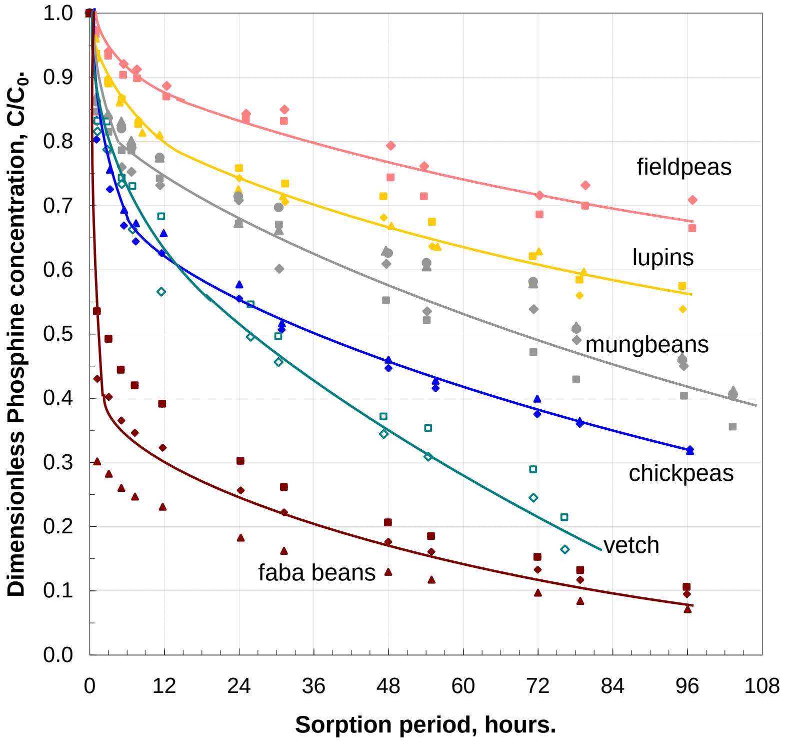

Figure 3.2.3. Illustration of the influence of grain type on batch phosphine adsorption for pulses (grain; 60% e.r.h., 25ºC, 95% filling ratio, initial concentration of 1g.m^{-3} as if flask was empty).

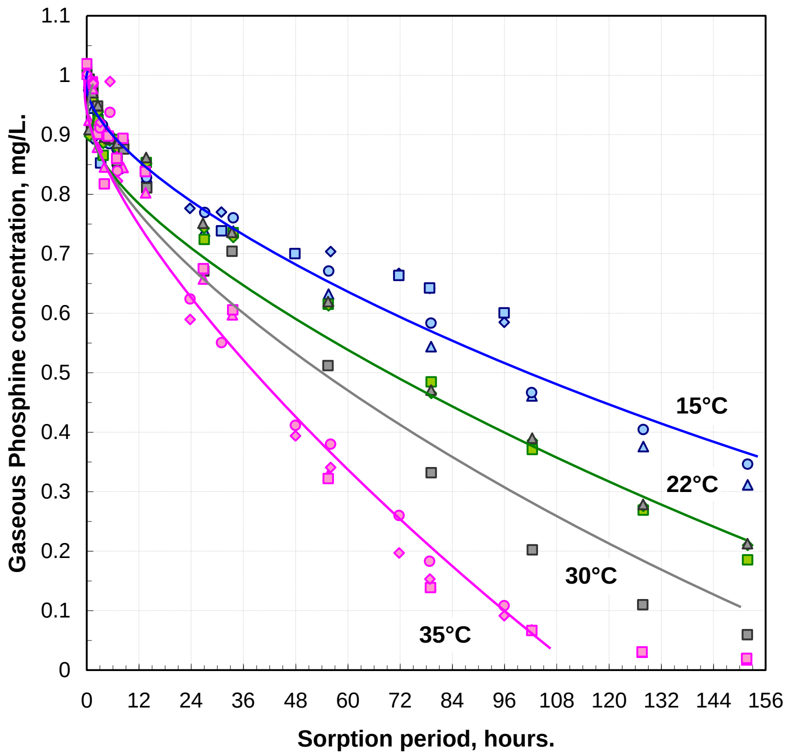

Figure 3.2.4. Illustration of the influence of grain temperature on batch phosphine adsorption for ASW wheat (grain; 95% filling ratio, initial concentration of 1g.m^{-3} as if flask was empty, 60% e.r.h. which gives grain moisture contents of 13.2%, 12.8%, 12.4%, 12.2% for 15, 22, 30, 35ºC respectively).

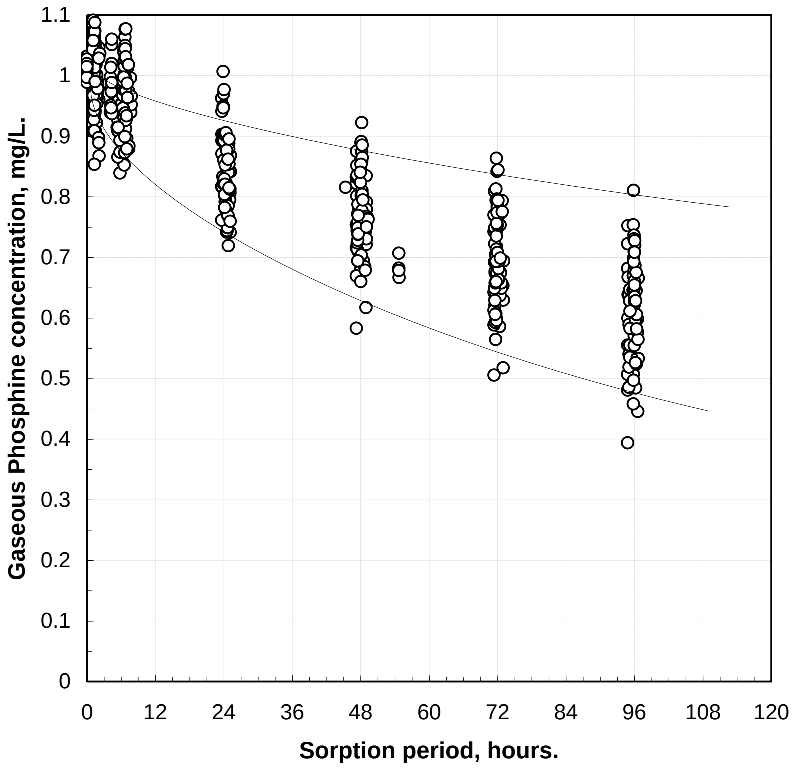

Figure 3.2.5. Illustration of the influence of 'field batch' on batch phosphine adsorption for ASW wheat variety Vulcan from 50 grower samples (grain; 95% filling ratio, initial concentration of 1g.m^{-3}, grain moisture, 9.3-11.8% (av.

10.9%); protein content, 8.2-11.3% (av. 9.8%); treatment temperature, 25°C; and a harvest to treatment age of 2 to 28 weeks).

Fan forced reticulation can be used to distribute fumigants effectively throughout grain stacks, especially when a fumigant is rapidly adsorbed by a particular grain type. Several modern fumigants are based on ethyl formate and exhibit rapid adsorption characteristics accordingly. Fan-forced reticulation can enables the fumigant to penetrate a grain stack against sorption losses. In practice, recirculation within a gas-tight system is prevalent, in order to contain the toxic fumigant gas for OHS&E requirements. This project defined the sorption kinetics of EF by wheat for both batch (finite-volume) and 1D airflow conditions, which are illustrated on Figures 3.2.6 and 3.2.7 respectively. The Figures demonstrate how EF vapour concentrations will rapidly decrease to non efficacious levels (Figure 3.2.6) without continual ‘topping up’ by entrainment with a forced airflow (Figure 3.2.7). Even still, the sorption of EF from a flowing airflow can be too dominant if the reticulation system is not designed appropriately.

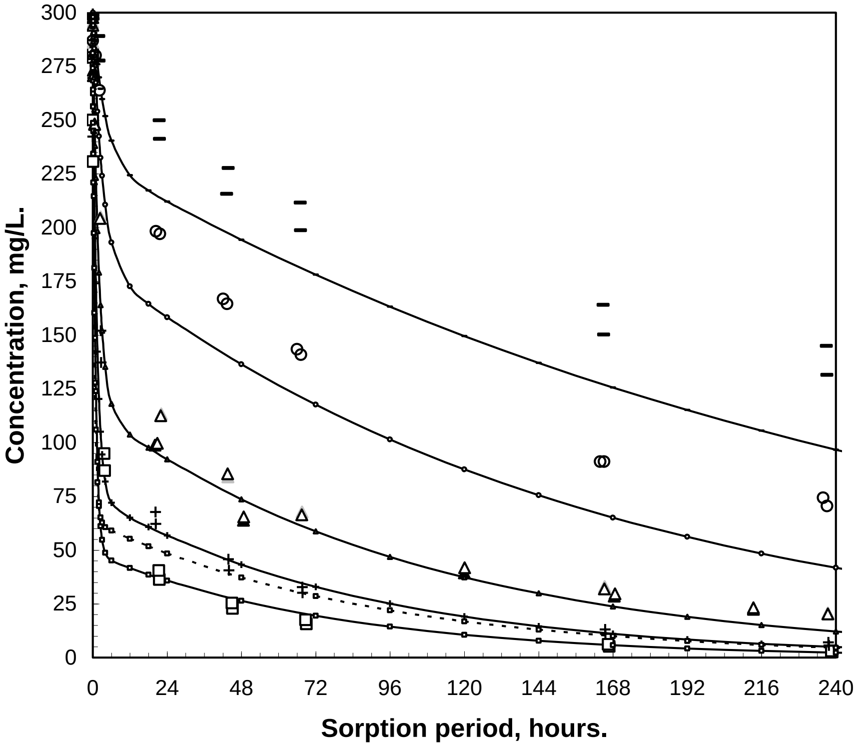

Figure 3.2.6. Batch adsorption of gaseous ethyl formate by ASW wheat (12% moisture w/w, 22°C) for different filling ratios with an initial concentration of approximately 300 mg L^{-1}. The symbols indicate filling ratios as follows:- □80%, + 60%, Δ 40%, ○ 20% and ☐ 10%. Lines indicate fit of model (see below).

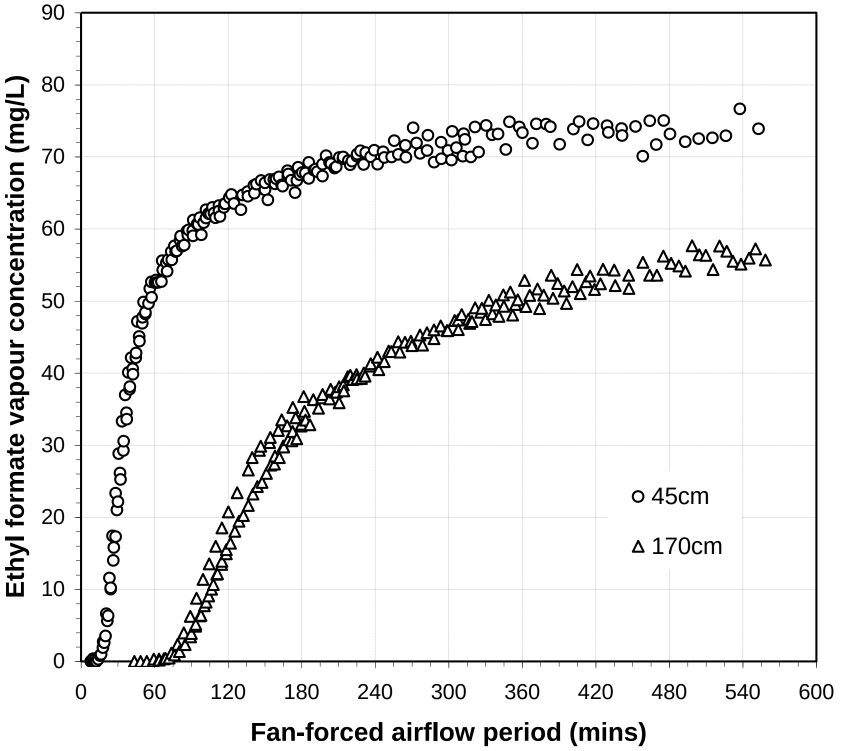

Figure 3.2.7. Ethyl formate vapour concentrations measured at ○ 450mm and Δ 1750mm heights of a 1970mm column of wheat during fan forced flow of air at one gas change per hour, inlet EF concentration 78-80 mg.L^{-1}, 23-25°C, four repeat runs.

This project developed a 'mass transport' model for the kinetics of fumigant adsorption by grain from a gaseous mixture, in order to predict performance in commercial scale grain stores as a function of the various factors involved. The model was 'fitted' against the batch and 1D flow data sets presented in Figures 3.2.1 to 3.2.7, with a focus on wheat, which were measured at concentrations and exposures relevant to practical disinfestation and residue contamination. Experimental constraints prevented the independent determination of each component chemical reaction or diffusion rate involved in the overall sorption process, or phase equilibrium, so the form of the model was constructed on the basis of published evidence. The model utilised lumped-sum representations of individual transport rates and is illustrated schematically on Figure 3.2.8. The mass transport equations defining this model for one dimensional flow of air through a grain bulk are provided following Figure 3.2.8. This model was used to predict fumigant concentrations throughout industrial scale grain stores undergoing fan-forced fumigation, which are described in the field trial section of this report.

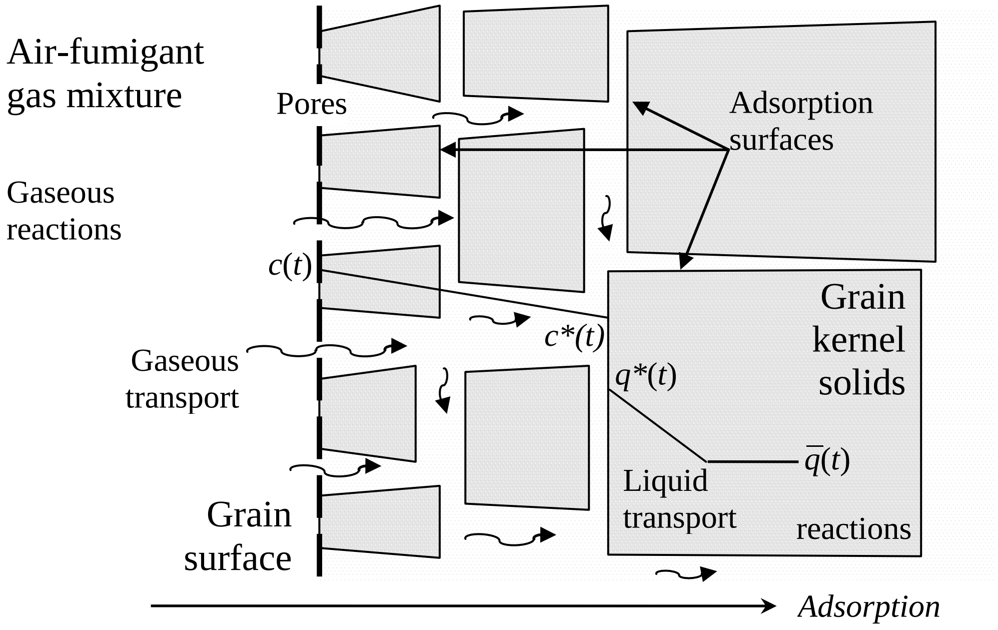

Figure 3.2.8. Diagram of the mass transfer model of fumigant adsorption by grain (model 16); gaseous fumigant intra-kernel linear mass transfer resistance, gaseous fumigant reaction, adsorbed liquid fumigant internal grain kernel linear mass transfer resistance, intra-kernel homogeneous consumption of fumigant, and linear partition relation representation of isotherm (Henry's law).

$$D_b \frac{\partial^2 c}{\partial z^2} - v_i \frac{\partial c}{\partial z} + A_2 c + A_3 \bar{q} - \frac{\partial c}{\partial t} = 0 \quad \ldots (19) \qquad \frac{\partial \bar{q}}{\partial t} + A_4 \bar{q} - A_5 c = 0 \quad \ldots (21)$$

$$A_1 = \left(k_{fA} + \frac{k_{fG} F}{\rho_g} \right) = \frac{m^3 A}{m^2 S\, hr}$$

$$A_2 = \left[r_{fA} + \frac{s_{sorp} k_{fA} k_{fA}}{\varepsilon A_1} - \frac{s_{sorp} k_{fA}}{\varepsilon} \right] = \frac{1}{hr}$$

$$A_3 = \frac{s_{sorp} k_{fA} k_{fG}}{\varepsilon A_1} = \frac{kgG}{m^3 A\, hr}$$

$$A_4 = \left[\frac{s_{sorp} k_{fG}}{(1-\varepsilon)\rho_g} - \frac{s_{sorp} k_{fG}^2 F}{A_1 (1-\varepsilon)\rho_g^2} - r_{fG} \right] = \frac{1}{hr}$$

$$A_5 = \frac{s_{sorp} k_{fG} k_{fA} F}{A_1 (1-\varepsilon)\rho_g^2} = \frac{m^3 A}{kgG\, hr}$$

The nomenclature for the above set of equations is as follows

c	intergranular air concentration of fumigant (gF m^{-3} or mgF $litre^{-1}$)
t	time (hr);
z	linear dimension defining flow direction and scale
ε	porosity of the bulk grain is ($m^3 m^{-3}$)

v_i	interstitial velocity of the air through the grain
s_{sorp}	specific surface area for sorption is(m^{2}m^{-3})
k_{fA}	mass transfer coefficient of gaseous fumigant in air to grain (gF m^{-2} hr^{-1})
r_{fA}	rate of first order “reaction” of gaseous fumigant in air (gF m^{-3} hr^{-1})
D_b	flow dispersion coefficient of the grain bulk (m^2 hr^{-1})
ρ_g	“true” density of grain kernels (kgG$^-$ m^{-3}G)
$\bar{q}$	mean fumigant concentration in whole grain kernels(gF kgG^{-1}),
r_{fG}	rate of first order “reaction” of adsorbed fumigant in grain (gF kgG^{-1} hr^{-1})
k_{fG}	mass transfer coefficient of adsorbed fumigant within grain (gF m^{-2} hr^{-1})
F	partition factor

3.3 Distribution and dispersion of fan-forced flow in grain

In summary, this project developed a mathematical model to address the ‘spreading and diluting’ of sorptive fumigants as they are pumped through three dimensional grain stacks and also incur flow dispersion. An experimental program was conducted to define dispersion coefficient values for bulk grain. This modelling and experimental effort demonstrated that these phenomena are the significant factors for modern fumigants based on ethyl formate.

Forced distribution refers to pumping fumigant throughout a grain mass. Fan-forced fumigations are well recognized as providing a good means to distribute fumigants throughout grain bulks and have been used with methyl bromide and to a lesser extent phosphine. Such systems involve relatively small fans approximately 1/50 to 1/10 the size of aeration fans and change the intergranular gas of a grain mass in 15 minutes to 12 hours, although slower distribution times are used for some scenarios. For most practical reticulation layouts, the fumigant does not treat each tonne of grain within a store equally. The evenness of the gas exchange is a result of the flowfield that is created by the reticulation system duct layout and the grain stack shape and dimensions. A simple flow-field is illustrated on Figure 3.3.1. This unevenness of fumigation is critical for rapidly adsorbing fumigants such as ethyl formate (EF), which is being developed as several commercial products at present (VaporMate, Eranol, GL02). This project developed a mathematical model of fan-forced flow of sorptive fumigants, including the capacity to account for the non-uniform flowfield effect. The model was used to predict the effectiveness of various fan-forced systems to distribute ethyl formate vapour throughout typical large scale grain stores where the fast insecticidal affect of EF is likely to be used. The mathematical form of the model was provided in section 3.2. An example of its application with the flowfield issue included in illustrated on Figure 3.3.2.

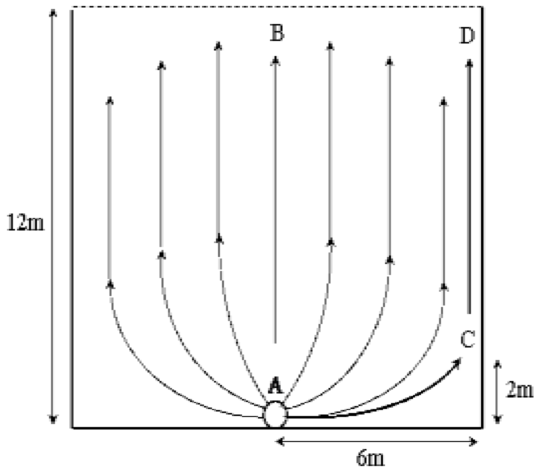

Figure 3.3.1. A two-dimensional schematic of a flowfield occurring in a fan-forced fumigated grain store.

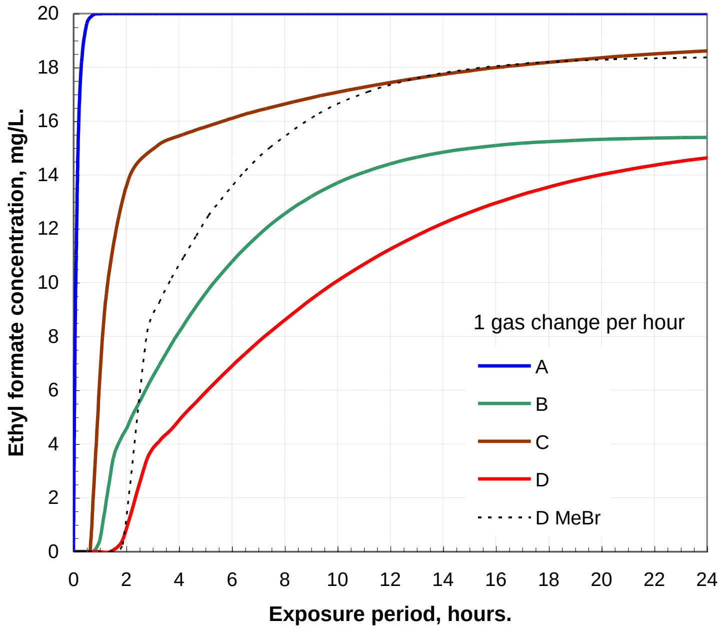

Figure 3.3.2. Ethyl formate concentrations at various positions in a flowfield presented on Figure 3.3.1, showing how the least-served location in the store (point D) will experience a substantially lower EF dose.

Another key issue for fan-forced reticulation of fumigants through grain stacks is the 'spreading' of the ensuing fumigant concentrations in the direction of flow as they are pumped through the grain stack. This is referred to as (longitudinal) flow dispersion, which occurs due to repeated processes of localized retarding of flow in 'dead-ends', parallel channels of longer distance, turbulence and "shuffling" of molecules which flow through a packed bed during bulk flow. This phenomena is a characteristic of the packed bed (or porous media) and intergranular fluid, and is defined by a coefficient which is a function of flowrate. This coefficient had not been defined for bulk grain and so this project measured this property to address the performance of modern fumigants, especially EF based. The use of this term in the mathematical model is presented in the equations of section 3.2.

The experimental apparatus used for measuring the longitudinal dispersion coefficient of bulk grain is illustration on Figure 3.3.3. This was composed of a sealed PVC circular tube with a height of 1,970mm and inside diameter of 108mm, fitted with matching PVC end-caps. The tube was fitted with septum based gastight gas sampling ports above an internal perforated metal sheet which supported the grain column. Airflow rates were adjusted and dispersion coefficients determined from the 'spreading' of pulses of predominantly non adsorbing CO_2. A typical set of experimental results is presented on Figure 3.3.4.

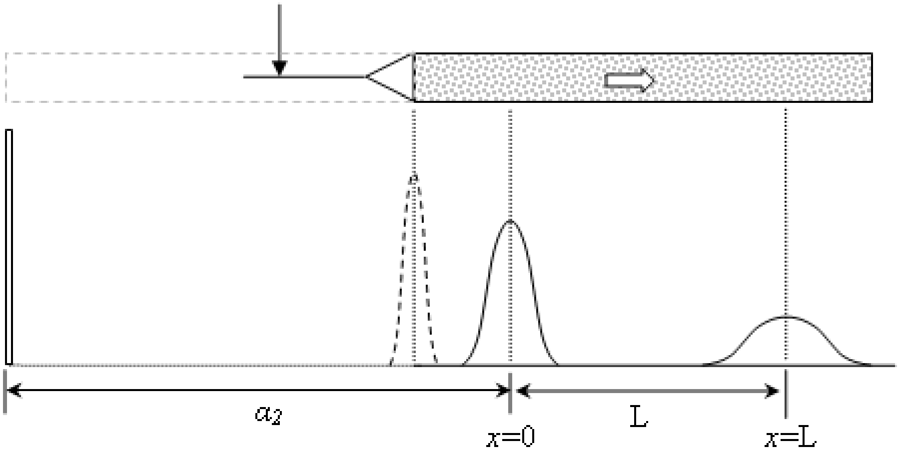

Figure 3.3.3. Schematic representation of the experimental grain column with purging airflow used to measure the longitudinal dispersion of air as it flows through a packed bed of grain, with an impulse input of CO2 concentration.

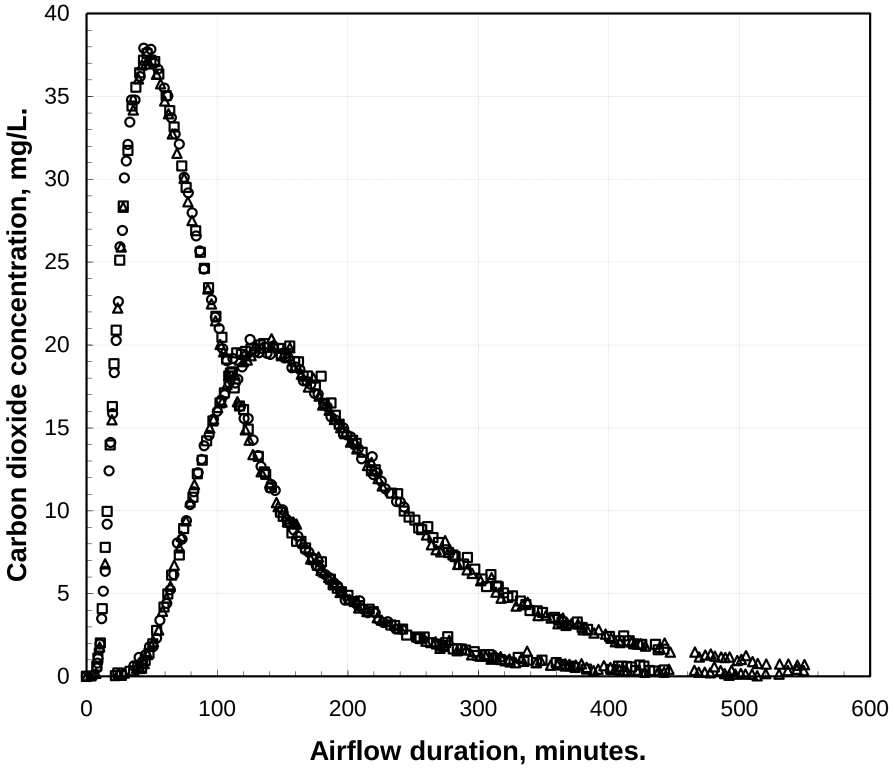

Figure 3.3.4. Example experimental results measuring the longitudinal dispersion of CO_2 entrained in a $20ml.min^{-1}$ airflow passing through an experimental column of wheat. The CO_2 concentrations were measured at 450mm and 1750mm above the base of the wheat column where the 'impulse' injection of CO_2 was made.

3.4 Efficacy predictions and resistance selection

In summary, efficacy modelling of this project demonstrated that the range in phosphine concentration profiles observed in fan-forced large grain silos dosed with aluminium phosphide derived PH_3, does not result in a corresponding wide range in efficacy achieved. Fumigations failures and possible resistance selection is unlikely with phosphide tablet reaction based dispensing, but the growing trend of 'instant release' technologies (generators, Eco_2Fume) can incur these risks. Also, the distribution of PH_3 was more critical to disinfestation failure than resistance status with the longest disinfestation periods relating to location, for the fumigation system studied.

Disinfesting grain with phosphine requires exposing any insects present for sufficient time to completely kill the population. The mortality response of insects to controlled exposures has been well defined by various laboratory investigations and mathematical models that quantify mortality based on these results have been developed. However, practical fumigations experience phosphine concentrations that vary substantially and how well disinfestation is achieved has not been clear accordingly. Practical fumigation performance is focussed on ensuring that phosphine concentrations are achieved throughout a store for sufficient time and it is not common to measure insect numbers before or after fumigation due to cost and measurement difficulties. Using a mortality model to relate measured PH_3 dose to mortality outcome, this project investigated disinfestation performance corresponding to phosphine concentrations measured in various industrial field trials. Noting that these measured results include the influence of all fumigant transport phenomena; application rate, distribution, sorption and leakage. Then, disinfestation predictions for a silo PH_3 fumigation model were made, where different levels of these phenomena were considered. Factors such as phosphine application technology, sorption and resistance status were included. A field trial based example of this 'analysis tool' is described here.

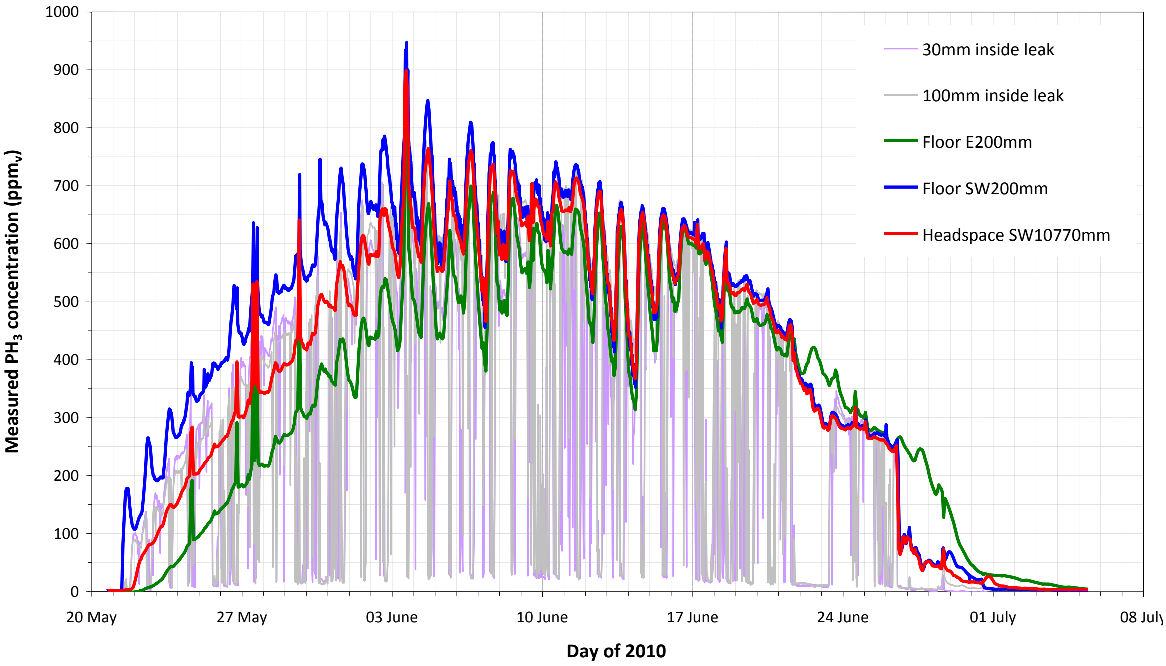

Figure 3.4.1. Selection of phosphine concentrations measured in the headspace, floor and near a leak in the 1500 tonne silo trial at 'Woodlawn' property, Coreen, NSW during May-June-July 2010. Phosphine was distributed by a fan-forced recirculation system from an AIP 'continuous' source.

Figure 3.4.1 illustrates a selection of PH_3 concentration profiles measured in a field trial of this project. This particular trial involved a high quality gas-tight silo of 1500tonnes capacity, which was fumigated using a recirculated fan-forced PH_3 dispensing system, which is state-of-the-art fumigation equipment. However, a large controlled leak was introduced, so that the silo was not gas-tight for the trial, to investigate this key issue. This Figure presents five profiles (from 24) that show the strongest to weakest doses with the silo, throughout the five week fumigation period. Two of the profiles were measured at a controlled leak, introduced into the silo at a lower sight-glass (1600mm above the ground) which illustrates the poorest concentrations in the silo. The floor (inlet to grain stack) and headspace (outlet of grain stack) sampling positions demonstrated the 'classic' humped shaped profiles (see Figure 3.4.1); that result from PH_3 being generated from aluminium phosphide pellets for up to 15 days against sorption and silo breathing losses that increasingly dominate at the end of the fumigation. The sampling locations near the leak show the daily oscillation in concentrations, ranging from <30ppm$_v$ to 'the hump' values during a 24h daily cycle, as PH_3 is pumped throughout the grain stack.

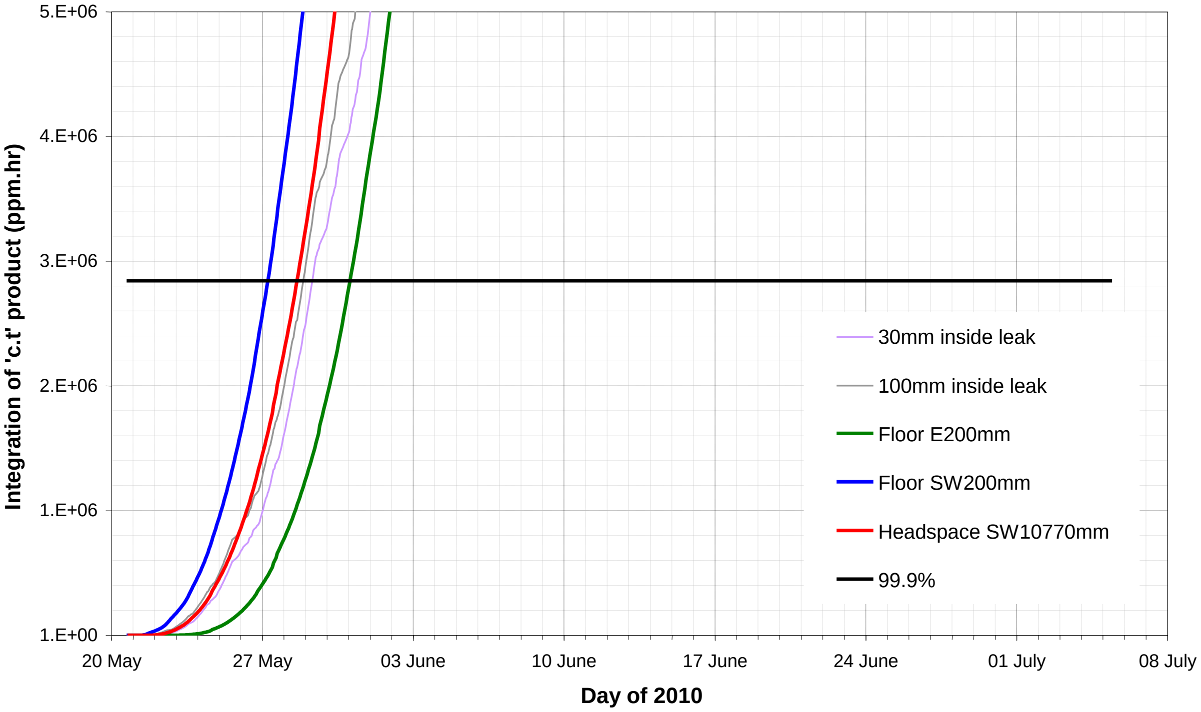

Figure 3.4.2. Prediction of time until 99.9% mortality of *Rhyzopertha dominica* (mildly resistant strain QRD569) predicted for the PH_3 concentrations measured at the headspace, floor and near leak in the 1500 tonne silo trial at 'Woodlawn' property, Coreen, NSW during May-June-July 2010 with fan-forced recirculation. The lethal time until 99.9% mortality ($LT_{99.9}$) occurs where the integrated ct product loci of each PH_3 sampling location in the silo intercepts the 99.9% isobole (horizontal line at 2.84×10^6).

Figure 3.4.2 presents mortality predictions for these 5 PH_3 profiles (using common plot colours between Figures). The time period until a common 99.9% level of mortality ($LT_{99.9}$) is estimated using a 'c^n.t' model (isobole), which was numerically integrated with respect to exposure time (x-axis) until the 'c.t' product is achieved. This time-step integration ensures that the interrupted exposure profiles (near the leak) provide a reasonable estimate of final mortality (as described above). These 'c^n.t' models had been developed from laboratory bioassay data (QDPIF primarily). The intersection of each PH_3 profile integration plot with the horizontal 99.9% ‘c.t’ level, determines the $LT_{99.9}$. Figure 3.4.2 presents the accumulating integrations for each PH_3 profile, which intuitively indicates the progressive death of a population. This Figure shows how $LT_{99.9}$ estimates range from 7-10 days across these five profiles, which is a comparatively small range. Most significantly, the $LT_{99.9}$ predicted at the silo leak was not the longest or inadequate. This results from the peaks of the daily PH_3 profile oscillations at the leak, being roughly twice that of the easterly floor (Floor E200mm) location and in the critical 100-350ppm_v band, during the initial eight days of the fumigation.

In this project, the disinfestation prediction method described above was used to analyse if practical fumigations could select for resistance. To illustrate this analysis, the above 5 PH_3 profiles were integrated using ‘c.t’ correlations for known resistant strains of stored product insects (QDPIF data). The $LT_{99.9}$ results are presented in Table 3.4.3. In this particular field trial example, these results indicate that there was negligible selection pressure incurred, with the difference between $LT_{99.9}$ for susceptible strains and strongly resistant strains being 7-11 days at the poorest dosed location in the silo (Floor east 200mm). For these ‘state of the art’ industrial silo fumigations, excess phosphine is administered that results in concentrations well above 400ppm_v in most parts of a silo, which is an asymptotic limit above which mortality rates or extents do not differ significantly. Mathematically, this method was applied to various PH_3 doses of various application approaches, both measured and model predictions, to analyse disinfestation outcomes. This table shows how distribution of PH_3 is more critical to survival than resistance status with the longest disinfestation periods relating to location, for this fumigation system.

Table 3.4.3. Prediction of time until 99.9% mortality ($LT_{99.9}$) for different insect species and strains of different PH_3 resistance status, predicted for the PH_3 concentration profiles measured in the 1500 tonne silo trial at ‘Woodlawn’ property, Coreen, NSW during May-June-July 2010 with fan-forced recirculation. The lethal time until 99.9% mortality ($LT_{99.9}$) occurs where the integrated ct product loci of each PH_3 sampling location in the silo intercepts the 99.9% isobole (horizontal lines).

Insect species	Strain	Resist status	PH_3 sampling position in silo									
			30mm inside leak		100mm inside leak		Floor East 200mm		Floor SW 200mm		Headspace SW 10770mm	
			d	**hr**	**d**	**hr**	**d**	**hr**	**d**	**hr**	**d**	**hr**
S. oryzae	LS2	nil	6	148.9	6	131.0	7	173.4	5	118.2	6	131.6
S. oryzae	QS0335	strong	9	205.9	8	195.0	10	245.7	7	158.5	8	188.6
R. dominica	QRD369	mild	7	172.5	7	157.4	9	204.0	6	130.7	7	153.8
R. dominica	QRD569	strong	9	207.3	8	196.8	11	249.9	7	157.6	8	190.0

3.5 Performance of an integrated fan-forced PH_3 dispensing system with aeration cooling; field trials, model validation data, and commercial collaboration

In summary, this project conducted a series of field trials that defined the performance of an integrated fan-forced PH_3 fumigation and aeration-cooling system, demonstrating strong disinfestation and repeat fumigation prevention characteristics of this combination. Furthermore, these trials provided high quality data sets for 1) evidence based identification of the main phenomena occurring in (large) silo fumigations, and 2) validation of computational fluid dynamics models (CFD) of fan-forced fumigations.

Phosphine based silo fumigation technology has been studied for over 40 years, yet the occurrence and causes of inadequate fumigations are not definite and many anecdotal explanations exist. Fumigation performance is assessed by maintenance of PH_3 concentrations and a variety of phenomena have been attributed to causing inadequate doses. This project included a series (4) of field trials to 1) define the performance of an integrated fan-forced PH_3 fumigation and aeration-cooling system, and 2) provide high quality data sets to conclusively identify the main phenomena occurring in (large) silo fumigations and causes of fumigation failures. A complementary objective was to obtain appropriate data for validation of computational fluid dynamics models (CFD) of fan-forced fumigations for an auxiliary CRC project (No 50091 "Technology to overcome inadequate fumigations and resistance selection"), which had overlapped with this project (No. 50059) due to drought preventing access to large silos of grain for earlier conduction of the trials of this project (50059). The trials were conducted at the 'Woodlawn' property (silo No. 6), Coreen NSW (40km north of Corowa) from 21st May to 5th July 2010 in a large 1829m^3 (1500t) aerated gastight silo with a fan-forced phosphine (PH_3) fumigation system with recirculation.

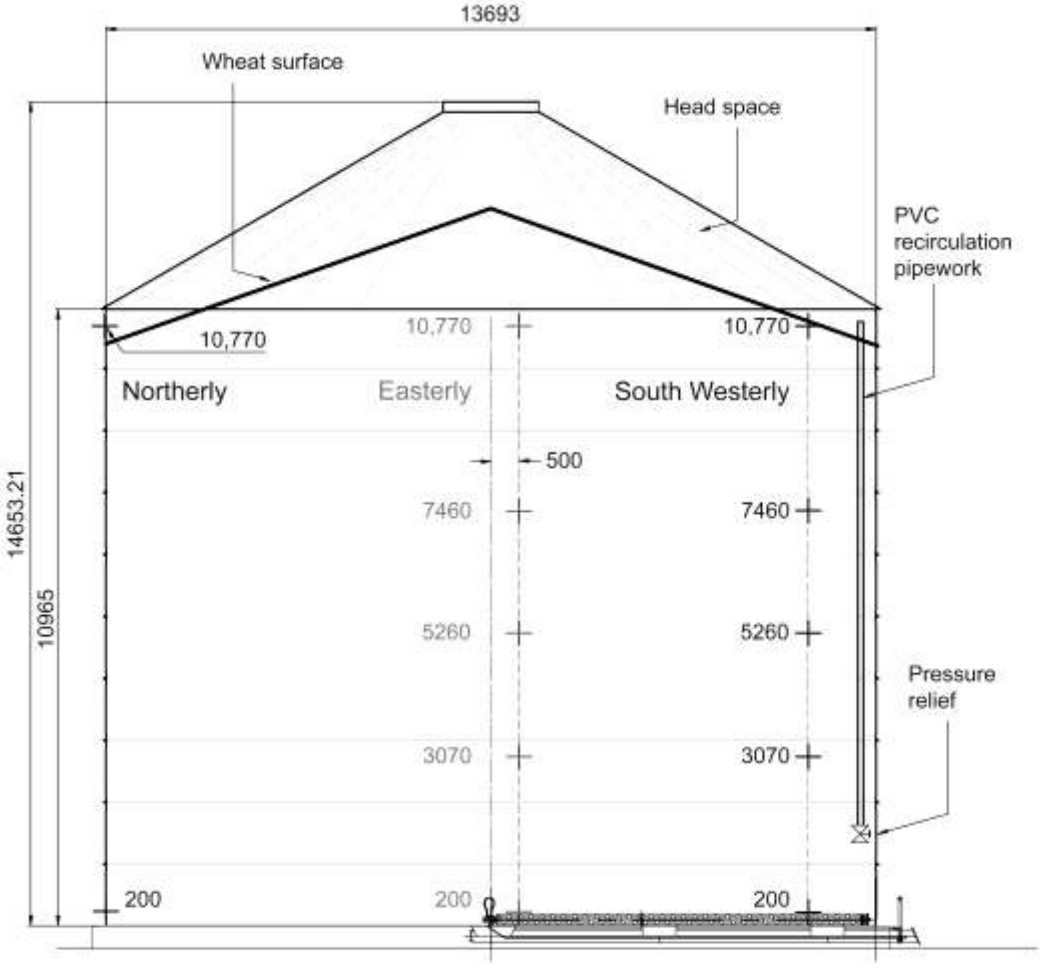

Figure 3.6.1. Elevation view of trial silo illustrating the locations of the 14 PH_3 sampling tubes, recirculation pipe-work, pressure relief valve; as well as silo dimensions and silo type (Kotzur, Model GP 18-10, galvanized steel with concrete base, nominal wheat capacity 1,500 tonnes).

The experimental effort of this trial measured the characteristics of phosphine concentration trends throughout the silo during fan-forced fumigations and demonstrated how local weather events influenced these trends. The experimental design measured the spatial distribution of PH_3 throughout the grain from the aeration duct introduction point, while determining the extent of flowfield dilution, leakage, ‘silo breathing’ and sorption losses with respect to position and time throughout the fumigation. Also, the design measured the distribution of PH_3 throughout the grain adjacent to the deliberately introduced large leak with respect to position and time throughout the fumigation. The concentration measurement frequency was matched to the rates of change of the causes of PH_3 distribution and any interruptions. In particular, influences such as; wind, solar radiation, ambient air temperature, rain, air exchange, barometric pressure, etc were measured to quantify how these claimed influences contribute to trends that cause fumigation problems. The layout and dimensions of this silo are illustrated on Figures 3.6.1 and 3.6.2.

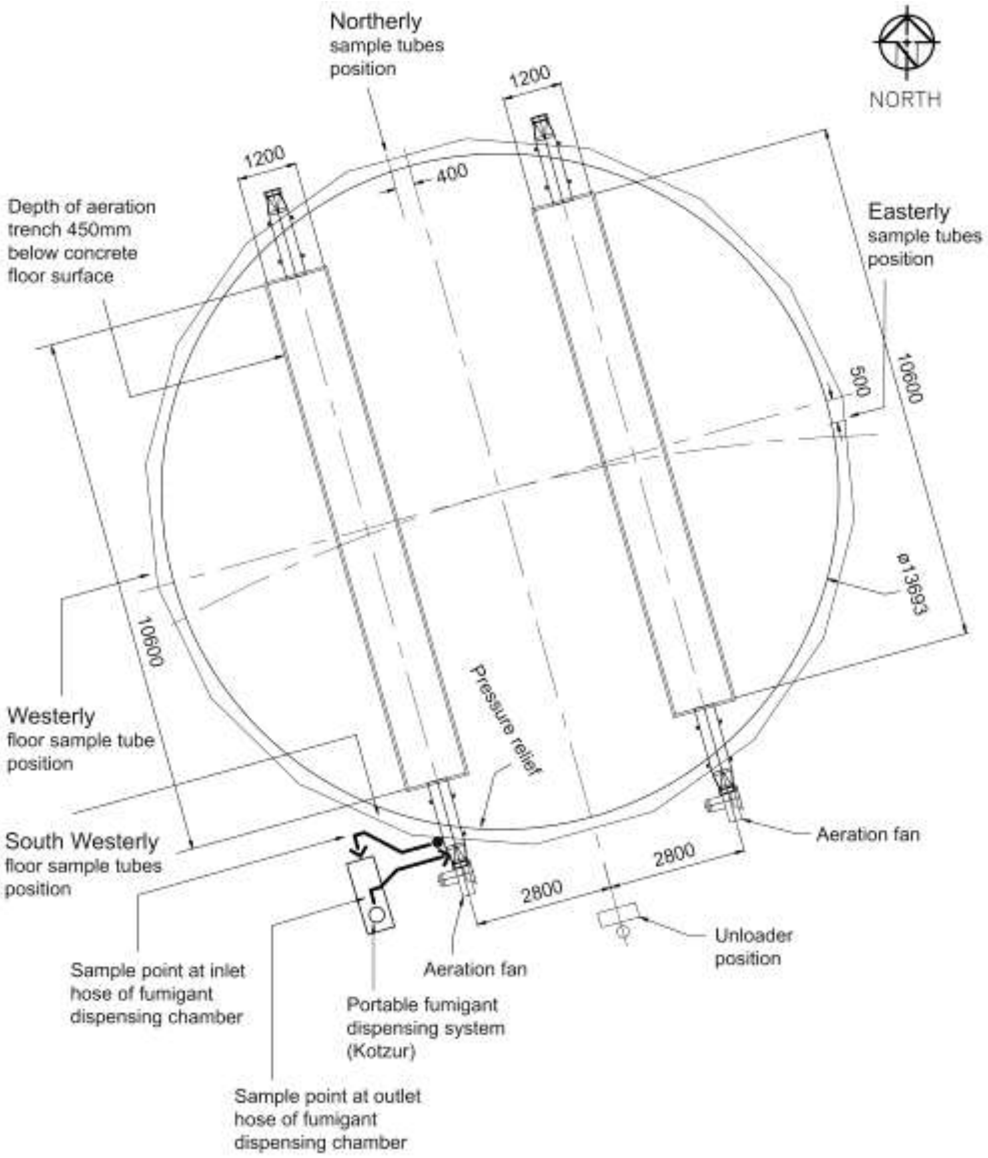

Figure 3.6.2. Plan view of trial silo illustrating the locations of the 14 PH_3 sampling tubes, recirculation pipe-work, pressure relief valve, portable fumigant dispensing system; as well as silo dimensions (Kotzur, Model GP 18-10, galvanized steel with concrete base, nominal wheat capacity 1,500 tonnes).

Typical phosphine concentration profiles measured throughout a field trial were presented and explained on Figure 3.4.1 above; for a selection of sampling positions that illustrate the range of profiles observed (and to avoid a crowded graph). Some averaged concentration profiles are shown on Figure 3.6.3. The relationship between the profile characteristics with various weather events and previously claimed mechanisms causing these profiles were analysed. A key technical simplification afforded with some of the fan-forced recirculatory trials, was that the recirculation of air-PH_3 meant that the concentrations throughout the silo were mixed and roughly even for a given point in time. This system removes from the validation analysis other previously referred to mass transport processes; natural (passive) convection, molecular diffusion, and 'chimney' effects. The main findings are summarized here.

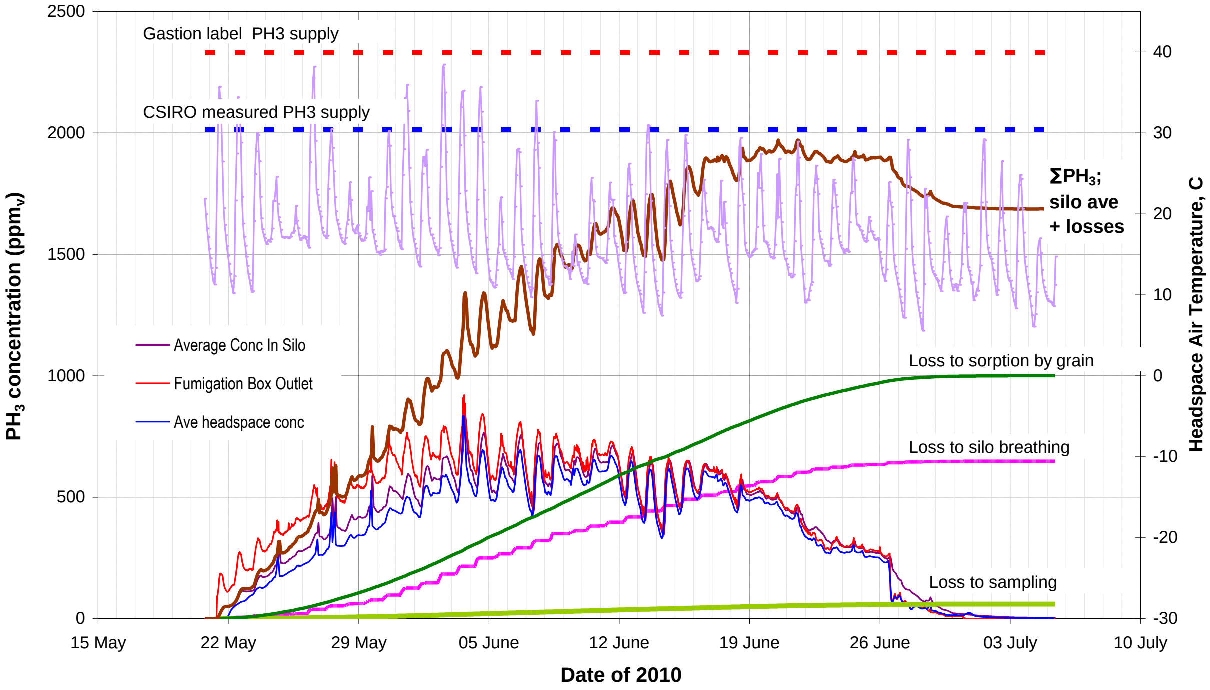

Figure 3.6.3. Phosphine 'mass balance', expressed in terms of PH_3 concentrations for the May-June-July 2010 1500 tonne silo trial at 'Woodlawn' property, Coreen, NSW. Phosphine was distributed by a fan-forced recirculation system from an AlP 'continuous' source. Silo headspace air temperatures measured during trial illustrate the mechanism of silo breathing based PH_3 loss.

The causes of the overall 'hump' shape of the profiles and the absolute value of concentrations were demonstrated by performing a PH_3 mass balance on the silo for the trials, which established that the mechanisms of sorption and silo breathing accounted for profiles predominantly. Silo breathing refers to the expansion and contraction of the internal air in the silo due to solar heating and night time heat losses. This PH_3 'mass balance' is illustrated in terms of PH_3 concentrations on Figure 3.6.3. The amount of PH3 supplied by the AlP tablets was calculated from the claimed amount from the product label and measured at CSIRO, with both values expressed as concentrations for the volume of air in the silo and recirculation system. The sorption loss was determined from the mathematical model described above (section 3.2) for the wheat temperature and moisture conditions of the trial. The 'silo breathing' loss was determined from the internal silo headspace air volume expansion during solar heating according to the headspace temperature displayed on Figure 3.6.3, where the PH_3 is lost at the PH_3 concentration of the headspace. The sampling loss refers to the amount of air withdrawn by the CSIRO experimental system. The sum of the measured average silo concentration profile and the progressive tally of losses as a function of time (brown line) reaches a maximum by 20th June, which aligns well with the amount of PH_3 administered by the AlP tablets (CSIRO measured supply, blue dashed line), indicating that the main phenomena involved in this 'state of the art' fumigation were identified. A key point is the large role that sorption played in suppressing PH_3 concentrations. Sorption cannot be 'designed out' of a system and cold dry wheat is least sorptive grain scenario (see section 3.2 above).

The daily oscillation of PH_3 concentrations in the silo overlaying the overall hump shaped profile correlated with solar radiation, and did not show any relationship to wind or barometric pressure. This correlation is demonstrated on Figures 3.6.4 and 3.6.5, where the daily oscillating silo headspace air temperature profiles correlated with the PH_3 concentrations unerringly. This correlation indicated that the silo breathing based PH_3 loss and dilution via pressure relief and controlled leak air exchange could be a significant contributor to PH_3 loss, which was supported by calculation as presented on Figure 3.6.3. This component loss mechanism was confirmed experimentally, by over-riding this headspace dilution effect by opening the silo hatch which suppressed the oscillations.

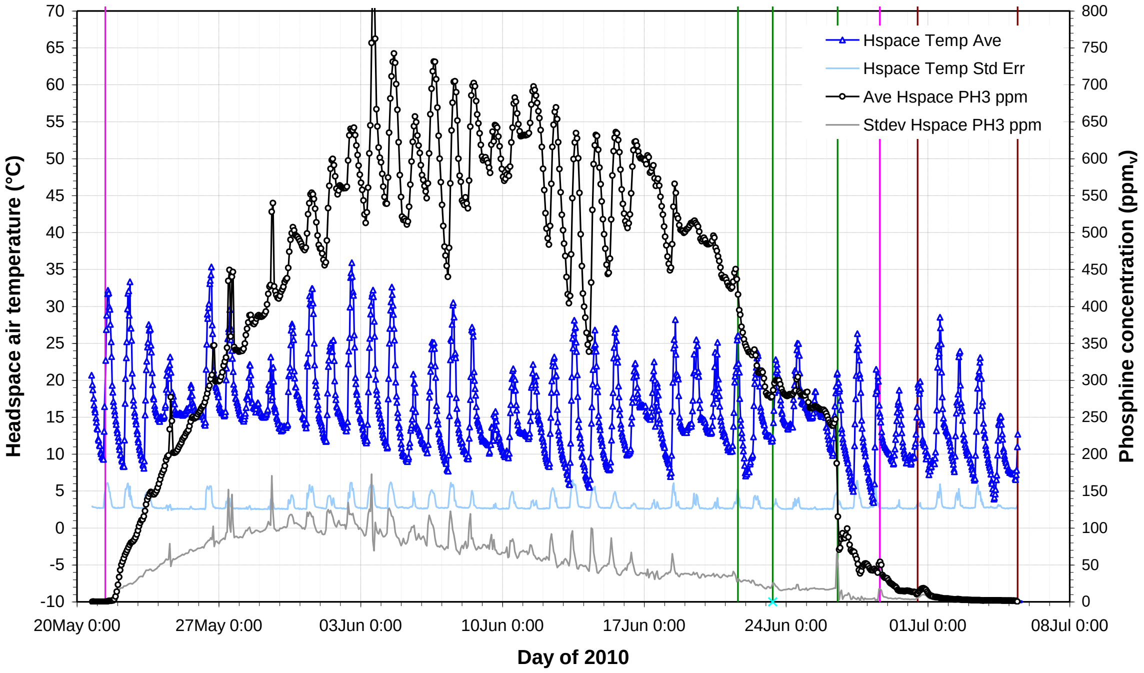

Figure 3.6.4. Average silo headspace phosphine concentrations and air temperatures measured during May-June-July 2010 in the 1500 tonne silo trial at 'Woodlawn' property, Coreen, NSW. Phosphine was distributed by a fan-forced recirculation system from an AIP 'continuous' source. Green lines indicate the opening and closing of silo hatch; pink recirculation started and stopped, brown purging.

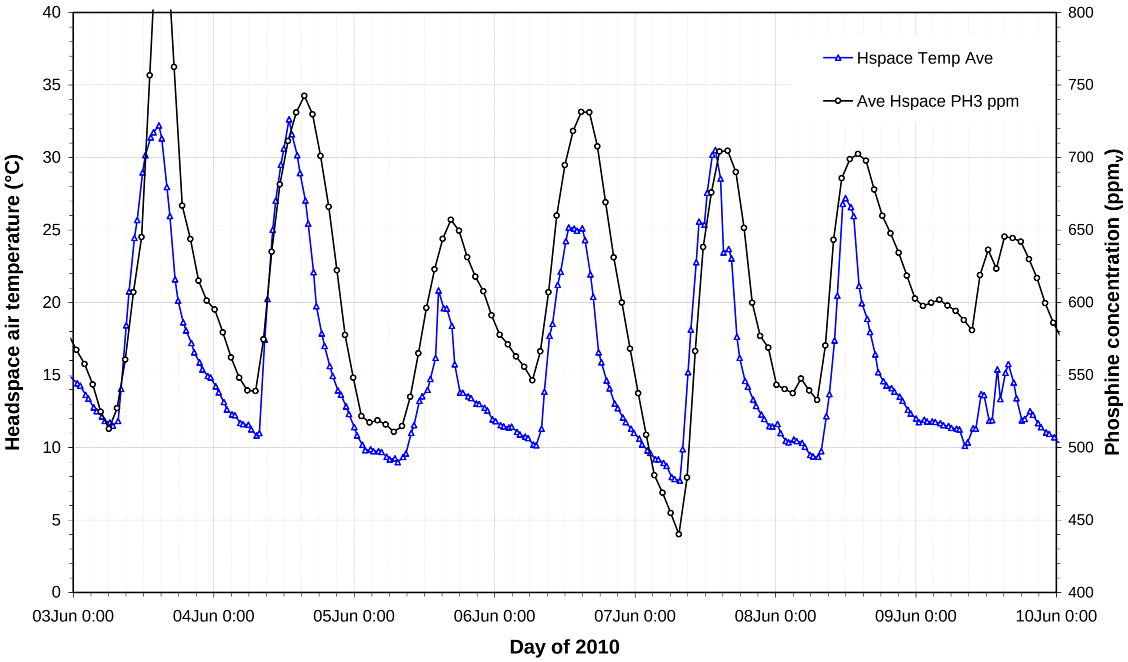

Figure 3.6.5. Relationship between average silo headspace phosphine concentrations and air temperatures measured during the first week of June 2010 in the 1500 tonne silo trial at 'Woodlawn' property, Coreen, NSW. Phosphine was distributed by a fan-forced recirculation system from an AlP 'continuous' source.

The field trials of this project also defined the performance of an integrated fan-forced PH_3 fumigation and aeration-cooling system, quantifying the performance characteristics of this technology combination in collaboration with Kotzurs Pty Ltd. This collaboration has provided the 'proof' for this flexible technology option for disinfestation and resistance management; and the associated modelling has enabled risk scenarios to be identified. The efficacy predictions of section 3.4 alongside the PH_3 concentration profiles measured for 'label rate' fumigations demonstrate its strong insecticidal performance and explained 'why these results were obtained'. On the counter-side, the strong PH_3 doses achieved with this system resulted in wheat with substantial amounts of adsorbed PH_3. When this wheat was delivered for trade, desorption of PH_3 to create concentrations above OHS standards at the receival stand, despite fan-forced purging, causing several rejections. Also, the strong role of sorption in grain fumigation highlighted the dependence of this system on 'continuous release' PH_3 sources (AlP) to overcome sorption losses in high temperature wheat or alternative grain types where the modelling predicts inadequate concentrations would result. Furthermore, 'instant' PH_3 dispensing technologies such as generators and cylinder dumps were also predicted to have inadequate doses as sorption would reduce PH_3 concentrations before disinfestation was complete.

4. Implications for stakeholders

This project has quantified each of the phenomena involved in applying fumigants in gas-tight industrial grain stores and demonstrated the significance of each via field trials and mathematical modelling. Industry can use the results of this project to improve fumigation practices and equipment designs to cost effectively achieve efficacious and safe grain disinfestation, including the prevention of resistance selection. As key industry representatives were participants in this project (bulk handling companies, grower equipment suppliers), these improvements are already being implemented. In particular, a commercial prototype system combining fan-forced phosphine fumigation with aeration-cooling in large silos (>1000tonne) addresses the problems identified and is being traded by an industry technology supplier (Kotzur).

The experimental determined data sets and mathematical models remain as ongoing contributions to the science and technology of grain storage and fumigation. These contributions were:

- A data set defining the mortality of representative stored product insects to "interrupted" PH_3 doses.
- An extensive data set quantifying phosphine, methyl bromide and ethyl formate sorption by grain.
- A mathematical model defining the kinetics of fumigant sorption by grain.
- A data set defining the intergranular gas flow dispersion coefficients of packed beds of grain.
- A computational fluid dynamics model of fan-forced fumigation based on the significant influences identified with field trials, including industrial scale validation of the fundamental mass transport equation set.
- Simulations of recirculated fumigation in silos.
- Field trial data sets describing phosphine distribution for a recirculated fumigation system in gas-tight silos and losses due to weather influences and grain sorption.
- Evidence based diagnosis of the significant mass transport phenomena that determine the distribution of fumigants in stored grain.
- Performance of a commercial industrial scale fan-forced fumigant dispensing system designed for implementation in large scale grain stores, with a focus on aeration-cooled silos (collaborative effort with manufacturer).

5. Recommendations

This project quantified the roles of the interrelated factors affecting fumigant doses within fan-forced fumigated grain stores (mortality, distribution, sorption, leakage) and developed models defining the efficacy of fumigant doses as applied in Australia which were validated with field trials. Based on these findings, the following recommendations are made.

- Make available to industry awareness of scenarios where fumigations will fail in gas-tight stores, even with fan-forced reticulation; 1) 'instant release' phosphine dispensing technologies (generators, cylinders), 2) fumigation of highly sorptive grains, and 3) inadequate distribution by fan-forced systems with poor duct layouts
- Make available to industry knowledge that fan-forced fumigation systems for phosphine can overcome inadequacies in gas-tightness of the store to a reasonable extent, as 'leaks' do not cause deficient fumigations if an adequate overall accumulated exposure is achieved. This is usually the case in reasonable practical fumigations, which means that considerable lenience in store gas-tightness can be afforded for effective disinfestation.
- The research results of this project in fan-forced fumigated stores illustrate that selection of PH_3 resistant strains of insects is predominantly affected by fumigant distribution versus sorption, and the analysis approach of this work should be continued for non fan-forced grain fumigation systems.
- A thorough quantification and field trial study on phosphine desorption is needed by industry to handle the conflict that good phosphine fumigations can result in growers or grain fumigators having the fumigated grain rejected due to OHS reasons.
- Some improvements in fan-forced fumigation systems are still required to create equipment that meets all requirements.

6. Abbreviations/glossary

Insert list of abbreviations of acronyms (for example)

ABBREVIATION	**FULL TITLE**
CRCNPB	Cooperative Research Centre for National Plant Biosecurity
EPP	Emergency plant pest
CFD	Computational Fluid Dynamics
PH_3	Phosphine gas
AlP	Aluminium phosphide (tablets)
EF	Ethyl formate (fumigant)
BHC	Bulk handling companies (of Australia)
GRDC	Grains Research and Development Corporation

7. Plain English website summary

Please complete table using plain English. This information will be published on CRCNPB's website for a public audience.

CRC project no:	CRC 50059
Project title:	Technology to overcome inadequate fumigations and resistance selection
Project leader:	James Darby
Project team:	○ Co-operative Bulk Handling of WA; Ernie Kostas, Graeme George, Alan Bone, Aaron Rhodes, Dean Scott, Phil Taylor. ○ CSIRO Ecosystem Sciences; James Darby, Stephen Beckett, Tracy Willis, Tiffany Cripps, Aaron Barrett, Ben Padovan, Julie Cassells ○ GrainCorp Operations Pty Ltd; Matthew Head, Robyn Reid, Warren Bremer, Bruce Cole ○ Kotzur Engineering; Andrew Kotzur, Murray Collis, Malcom Bruce, Kevin Hunt, John Bickerton ○ University of WA; Professor Liang Cheng, Dr Ming Zhao, Wei He, Dr Pat Morgan ○ Viterra SA; Greg Hopkins, Steve Buick, Geoff Masters, Merv Crossman, Grant Haines
Research outcomes:	○ Quantification of each of the phenomena involved in applying fumigants in gas-tight industrial grain stores and demonstrated the significance of each via field trials and mathematical modelling (e.g. sorption, silo breathing, leakage, flow dispersion). ○ A data set defining the mortality of representative stored product insects to "interrupted" PH_3 doses. ○ An extensive data set quantifying phosphine, methyl bromide and ethyl formate sorption by grain. ○ A mathematical model defining the kinetics of fumigant sorption by grain. ○ A data set defining the intergranular gas flow dispersion coefficients of packed beds of grain. ○ A computational fluid dynamics model of fan-forced fumigation based on the significant influences identified

	with field trials, including industrial scale validation of the fundamental mass transport equation set. ○ Simulations of recirculated fumigation in silos. ○ Field trial data sets describing phosphine distribution for a recirculated fumigation system in gas-tight silos and losses due to weather influences and grain sorption. ○ Evidence based diagnosis of the significant mass transport phenomena that determine the distribution of fumigants in stored grain. ○ Performance of a commercial industrial scale fan-forced fumigant dispensing system designed for implementation in large scale grain stores, with a focus on aeration-cooled silos (collaborative effort with manufacturer). ○ A commercial prototype system combining fan-forced phosphine fumigation with aeration-cooling in large silos (>1000tonne) addresses the problems identified and is being traded by an industry technology supplier (Kotzur).
Research implications:	○ The roles of the factors affecting fumigant doses within fan-forced fumigated grain stores (mortality, distribution, sorption, leakage) were diagnosed with laboratory data and modelling and validated with field trials. These results identified the main causes of fumigation failure and resistance selection with this fumigation system. ○ The experimentally determined data sets and mathematical models act as ongoing contributions to the science and technology of grain storage and fumigation which are listed here as follows. - A data set defining the mortality of representative stored product insects to "interrupted" PH_3 doses. - An extensive data set quantifying phosphine, methyl bromide and ethyl formate sorption by grain. - A mathematical model defining the kinetics of fumigant sorption by grain. - A data set defining the intergranular gas flow dispersion coefficients of packed beds of grain. - A computational fluid dynamics model of fan-forced fumigation based on the significant influences identified with field trials, including industrial scale validation of the fundamental mass transport equation set. - Field trial data sets describing phosphine distribution for a recirculated fumigation system in gas-tight silos and losses due to weather influences and grain sorption. - Evidence based diagnosis of the significant mass transport phenomena that determine the distribution of fumigants in stored grain. ○ A prototype commercial industrial scale fan-forced fumigant dispensing system designed for implementation in large scale grain stores, with a focus on aeration-cooled silos (collaborative effort with manufacturer) was developed and its performance defined. ○ The research results of this project in fan-forced fumigated stores illustrate that selection of PH_3 resistant strains of insects is predominantly affected by fumigant distribution versus sorption, and the analysis approach of this work should be continued for non fan-forced grain fumigation systems.
Research publications:	Darby J.A. (2005). Development of an Integrated Aeration-fumigation system; a feasibility study. Entomology technical report series, Contracted Report No 80 (Contracted to GRDC,

	Project CSE0005), 61 pages. Darby J.A. and Beckett S.J. (2007). How effective are non-continuous phosphine doses? In: Proceedings of the 4th Australian Postharvest Technical Conference, Perth, WA, 2006. Darby J.A., Cassells J.A. and Banks H.J. (2007). An overview of an extensive data set of phosphine sorption by grain. In: Proceedings of the 4th Australian Postharvest Technical Conference, 5-6th August, Perth, WA, 2006. Darby J.A. (2008). A kinetic model of fumigant sorption by grain using batch experimental data. Pest Management Science 64(5), 519-526. Beckett S.J. (2008). The Mortality Response of Sitophilus oryzae (L.) Eggs to Diurnal Interrupted Doses of Phosphine (PH3). In, Proceedings of the 8th International Conference on Controlled Atmosphere and Fumigation in Stored Products, Chengdu, China, September 21-26, Eds; Guo Daolin, Shlomo Navarro, Yang Jian, Tao Cheng, Jin Zuxun, Li Yue, Liu Yang and Wang Haipeng, Sichan Publishing House, pages 10-14. Darby J.A., Willis T.R. and Damcevski K. (2009). Modelling the kinetics of ethyl formate sorption by wheat using batch experiments. Pest Management Science 65(9), 982-990. Beckett S.J., Darby J.A. and Forrester R.I. (2010). The effect of diurnally interrupted doses of phosphine over four days on egg mortality of susceptible and resistant strains of Sitophilus oryzae (L.). Journal of Stored Products Research 46, 59-65. Beckett S.J., Darby J.A. and Forrester R.I. (In press). The effect of diurnally interrupted doses of phosphine on egg mortality of susceptible and resistant strains of Sitophilus oryzae (L.). Journal of Stored Products Research.
Acknowledgements:	The following collaborators are gratefully acknowledged for the contribution to the success of this project. o Co-operative Bulk Handling of WA; Ernie Kostas, Graeme George, Alan Bone, Aaron Rhodes, Dean Scott, Phil Taylor. o CSIRO Ecosystem Sciences; Stephen Beckett, Tracy Willis, Tiffany Cripps, Aaron Barrett, Ben Padovan, Julie Cassells o GrainCorp Operations Pty Ltd; Matthew Head, Robyn Reid, Warren Bremer, Bruce Cole o Kotzur Engineering; Andrew Kotzur, Murray Collis, Malcom Bruce, Kevin Hunt, John Bickerton o University of WA; Professor Liang Cheng, Dr Ming Zhao, Wei He, Dr Pat Morgan o Viterra SA; Greg Hopkins, Steve Buick, Geoff Masters, Merv Crossman, Grant Haines