

Abstract

Gandy, Steven Ray. Quicklime Stabilization of Belt-separated Swine Manure (Under the direction of John Classen and Sarah Liehr)

New treatment processes for animal waste management and utilization are required for safer and environmentally compatible operation of production facilities. The principal goal of this research was to determine the feasibility, both technologically and environmentally, and the influencing factors associated with quicklime (Calcium Oxide) stabilization of belt separated swine manure. Factors such as required dose, manure temperature, and other basic model parameters were studied to produce a biosolid product meeting the same requirements as set fourth in the Federal (US-EPA) regulations CFR 40 Part 503 for temperature, pH, and residual moisture.

Quicklime may be used to raise the pH of manure solids, thus initiating a stabilizing effect of killing pathogens, reducing vector attraction, and controlling odors. A range of 5 % to 15 % quicklime doses was tested on separated manure solids. The largest dose (15 %) yielded higher stabilization temperatures, a higher initial pH increase during mixing, and lower residual moisture in the stabilized product. Solids treated with doses of 10 % and 15 % quicklime can produce a stabilized product which meets the same requirements as Class A biosolid defined in Part 503 of the CFR 40. Manure treated with 10 % quicklime lost through volatilization approximately 80 % of the original ammonia over a period of 7 days. An additional 10 % was liberated over the next 21 days.

Stabilization pH occurs above 12 and nearly all ammoniacal nitrogen is in the form of ammonia. Consequently, ammonia volatilization was increased from approximately 0.005 $\mu\text{g} / \text{min g dry solids}$ for the raw manure to a maximum of 45 $\mu\text{g} / \text{min g dry solids}$ for a one liter stirred reactor following addition of 10% quicklime on a wet weight basis. This volatilization rate was not maintained after mixing due to limitations on diffusion of aqueous ammonia through the manure solids. Under steady state operation of a 15' X 6" auger reactor the maximum amount of ammonia removed was less than 20 % of the original ammoniacal nitrogen in separated manure solids over a three minute period and less than 1 % of the total nitrogen in the swine waste.

Heat balances around the auger reactor resulted in a calculated efficiency for the hydration of added quicklime. Greater hydration efficiencies occurred at warmer ambient temperatures and with wetter manures. Quicklime dosage rates between 10 and 20 % did not significantly affect hydration efficiency. Residual moisture content and pH requirements for Class-A biosolids were met by doses as low as 10 %; however stabilization at ambient temperatures below 16 $^{\circ}\text{C}$ did not raise temperatures above the required 50 $^{\circ}\text{C}$ for a 20 minute period.

Model equations for dependent reactor variables predicted for the steady state reactor point to the fact that warmer environments will have on average a better hydration efficiency, a higher reaction temperature, and increased ammonia volatilization. Consequently, warmer manure solids used in the stabilization process are more likely to result in a product matching the CFR Class-A biosolid requirements. Inlet manure temperature was assigned the greatest coefficient for each of these model equations, indicating a large sensitivity to this factor.

Continuous belt operation will produce the highest moisture manure possible for the belt system. With respect to quicklime utilization and product temperatures, the most efficient systems will combine this belt removal technique with a constantly warm in-house treatment scheme. A quicklime stabilization process such as studied here, using a 10 % quicklime dose, assuming an average solids output of 2 lbs / pig / day and a quicklime cost of \$ 100 / ton, would have a material cost of one cent per pig per day.

Quicklime Stabilization of Belt-separated Swine Manure

by
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Dedication

I would like to dedicate this work to my parents, Sybil Ray and Clinton Frasier Gandy. The pride and encouragement they have bestowed upon me have been a guiding light of encouragement in dark troubling times. My father is the man I have grown to respect more than any other I have known for his humility, wisdom, and his unending work ethic. A marine engineer for nearly three decades in the most troubling times the modern world has known and spending another in education to give his family a better start than he was afforded, he is my rock in the storm of life. My mother continually showed me loyalty, love, and forgiveness beyond what any person should have a right to expect. She ran to unseat the current local School Board representative, and eventually saved the rural portion of Onslow County's educational system from a sad state of neglect. Her versatility as a professional County Commissioner while maintaining her down to earth sensibilities are something I will spend the rest of my life trying to emulate. For these things, Mama and Pop, I am truly thankful.

Biography

Steven Gandy grew up in Sneads Ferry, North Carolina and attended Dixon High School in Holly Ridge, North Carolina. He worked as a commercial fisherman while attending Coastal Carolina Community College and the University of North Carolina at Wilmington. He graduated from North Carolina State University with Bachelor degrees in both Chemical Engineering (Bioscience option) and Chemistry in 1998. Steven graduated from North Carolina State University with a Master's of Science in Civil Engineering with a concentration in water and waster water treatment in 2000. Planning to graduate with a Ph.D. from the Department of Biological and Agricultural Engineering Department, North Carolina State University in the summer of 2004 his intentions are to work in the consulting field and attain his Professional Engineering Certification in 2005.

Table of Contents

List of Tables.....	VIII
List of Figures.....	IX
1 Introduction.....	1
1.1 Lime Stabilization.....	3
1.2 NH ₃ Loss Through Volatilization.....	3
1.3 Objectives.....	4
2 Literature Review.....	7
2.1 Separation by belt systems.....	8
2.2 Solid Product Classification.....	9
2.2.1 Class A Pathogen Requirements.....	11
2.3 Vectors.....	12
2.3.1 Options for Vector Attraction Reduction.....	13
2.4 Solid Product Development.....	13
2.4.1 Lime Stabilization.....	14
2.4.2 Acidification.....	15
2.4.3 Exothermicity.....	16
2.4.4 NH ₃ Loss Through Volatilization.....	16
3 Materials and Methods.....	18
3.1 PART 1 - Characterization.....	18
3.2 PART 2 - Mixing and Long Term Storage.....	18

3.3	Part 3 - Analysis of Initial Ammonia Volatilization.	21
3.4	PART 4 - Mass Balances for Volatilized Ammonia.	24
3.5	PART 5 – Steady State Auger System Analysis.....	25
	3.5.1 Heat Balance.....	28
	3.5.2 Statistical Analysis.....	33
4	Results and Discussion.....	35
4.1	Part 1 - Classification of Scraped Solids.....	35
4.2	Part 2 - Long Term Mixing and Storage Testing.....	36
	4.2.1 Mixing Temperature Profile.....	36
	4.2.2 Mixing pH Profile.....	38
	4.2.3 Post-mixing Ammonia Content.....	39
	4.2.4 Post Mixing Moisture.....	40
	4.2.5 Available Phosphorus.....	41
	4.2.6 Stabilized Product pH Profile During Storage...	42
	4.2.7 Residual Moisture.....	44
	4.2.8 Pathogens Kill and Regrowth.....	47
	4.2.9 Quicklime Stabilized [NH ₃].....	52
	4.2.10 Available P.....	56
	4.2.11 % Nitrogen.....	60
4.3	Part 3 - One Hour Bench Scale Tests.....	61

4.3.1	Air Analysis.....	62
4.3.2	Ammonia Volatilization from Raw Manure.....	63
4.3.3	Ammonia Volatilization at 10% quicklime.....	64
4.3.4	Duplicates at 15% quicklime.....	65
4.3.5	10% and 15% quicklime trials.....	67
4.4	Part 4 – Long Term Ammonia Volatilization.....	68
4.5	Part 5 - Steady State Auger Reactor.....	70
4.5.1	Airflow Rates and Ammonia Volatilization.....	70
4.5.2	Airflow and Temperature.....	73
4.5.3	Mixing Intensity and Temperature.....	74
4.5.4	Mixing Intensity and Ammonia Volatilization....	75
4.5.5	Moisture Content and Temperature.....	76
4.5.6	Moisture Content and Ammonia Volatilization..	79
4.5.7	Quicklime Dose and Temperature.....	81
4.5.8	Quicklime Dose and Ammonia Volatilization...	83
4.5.9	Insulated Operation.....	84
4.5.10	Manure Temperature.....	85
4.5.11	Heat Balance.....	86
4.5.12	Hydration Heat.....	88
4.5.13	Hydration Efficiency.....	88

	4.5.14Batch Reactor.....	89
	4.5.15Statistical Analysis.....	97
	4.5.16Direction for future studies.....	99
5	Conclusions.....	101
6	References.....	105
7	Appendix.....	109
	Table of abbreviations.....	109
	Part 1.....	110
	Part 2.....	111
	Part 3.....	120
	Part 4.....	130
	Part 5.....	132
	Sample Calculations for heat Balance.....	144
	Sample Calculations for Hydration Efficiency.....	145
	Batch Trial Data.....	148

List of Tables

Table 2.1	MCL for Class-A solids defined under the CFR40.....	10
Table 2.2.	Pathogen ceiling limits for Class-A and Class-B biosolids.....	10
Table 3.1.	Sampling frequency for acid traps used in Part 4.....	24
Table 3.2.	Defined variables for heat balance.	33
Table 4.1.	Average scraped and belt-separated manure parameters	35
Table 4.2.	Average metal concentration of separated swine manure.	59
Table 4.3.	Heat balance totals for the auger stabilization reactor.....	87
Table 4.4.	Independent and dependent variables used in SAS analysis	93
Table 4.5.	Significance of model variables for prediction of stabilized product moisture content for the prototype reactor.....	93
Table 4.6.	Significance of model variables for prediction of stabilized product temperature for the prototype reactor	94
Table 4.7.	Significance of model variables for prediction of ammonia volatilization per minute for the prototype reactor.....	95
Table 4.8.	Significance of model variables for prediction of the calcium oxide hydration efficiency for the prototype reactor on a per minute basis.....	97
Table 7.1	Abbreviations and acronyms	109

List of Figures

Figure 3.1. Schematic of mixing and sampling apparatus for Part 3.....	22
Figure 3.2. Schematic of auger reactor.....	26
Figure 3.3. Schematic of heat sinks and sources for the auger reactor.	29
Figure 4.1. Temperature profile for three manure moisture contents and three quicklime doses.	37
Figure 4.2. Initial pH change with quicklime addition.	38
Figure 4.3. Ammonia loss after 40 minutes of mixing. Percent removals are shown above each column.....	39
Figure 4.4. Moisture contents of raw and processed manure.	40
Figure 4.5. Reduction in available phosphorus during 40 minutes of mixing.....	41
Figure 4.6. pH decline for the low moisture (68%) trials.....	42
Figure 4.7. pH decline for the medium moisture (70%) trials.....	43
Figure 4.8. pH decline for the high moisture (72%) trials.	43
Figure 4.9. Residual moisture after treatment monitored weekly for the 5% quicklime dose.....	45
Figure 4.10. Residual moisture after treatment monitored weekly for the 10% quicklime dose.....	45
Figure 4.11. Residual moisture after treatment monitored weekly for the 15% quicklime dose	46
Figure 4.12 Coliform repopulation for the low moisture manure for 5%, 10%, and 15% quicklime additions over a 2 month storage period.....	48

Figure 4.13 Coliform repopulation for the medium moisture manure for 5%, 10%, and 15% quicklime additions over a 2 month storage period.....48

Figure 4.14 Coliform repopulation for the high moisture manure for 5%, 10%, and 15% quicklime additions over a 2 month storage period.....49

Figure 4.15. *E. coli* repopulation for the low moisture manure for 5%, 10%, and 15% quicklime additions over a 2 month storage period.....50

Figure 4.16. *E. coli* repopulation for the medium moisture manure for 5%, 10%, and 15% quicklime additions over a 2 month storage period.....51

Figure 4.17. *E. coli* repopulation for the high moisture manure for 5%, 10%, and 15% quicklime additions over a two month storage period.....51

Figure 4.18. Ammonia residuals for low moisture manure stabilized with 5%, 10%, and 15% quicklime. Raw ammoniacal nitrogen = 3625 µg / g dry solids.53

Figure 4.19. Ammonia residuals for medium moisture manure stabilized with 5%, 10%, and 15% quicklime. Raw ammoniacal nitrogen = 3540 µg / g dry solids.54

Figure 4.20 Ammonia residuals for high moisture manure stabilized with 5%, 10%, and 15% quicklime. Raw ammoniacal nitrogen = 2813 µg / g dry solids.55

Figure 4.21. 5%, 10%, and 15% quicklime stabilized low moisture manure observed and sampled weekly for 2 months. Raw available phosphorus = 8209 µg / g dry solids.57

Figure 4.22. 5%, 10%, and 15% quicklime stabilized medium moisture manure observed and sampled weekly for 2 months. Raw available phosphorus = 8659 µg / g dry solids.57

Figure 4.23. 5%, 10%, and 15% quicklime stabilized high moisture manure	
observed and sampled weekly for 2 months. Raw available phosphorus = 9326	
µg / g dry solids.	58
Figure 4.24. Total nitrogen for the raw manure and stored stabilized product eight	
weeks after quicklime addition.....	60
Figure 4.25. Duplicate experiments to measure cumulative ammonia loss from	
mixing of raw manure.	63
Figure 4.26. Cumulative ammonia volatilization for duplicates using a quicklime	
dose of 10%. Moisture content = 63%, Initial [NH₃] = 6.7 mg/g solids.	64
Figure 4.27. Cumulative ammonia volatilization for duplicates using a quicklime	
dose of 15%. (Moisture content = 64%, Raw [NH₃] = 6.85 mg/g solids).....	66
Figure 4.28. Ammonia volatilization for quicklime doses of 10% and 15%	
(Moisture content = 62%, Raw [NH₃] = 6.85 mg/g solids).....	67
Figure 4.29. Ammonia volatilization at 10% quicklime over an extended period	
after mixing. Raw ammoniacal nitrogen = 12.78 mg / g dry solids.	69
Figure 4.30. Ammonia capture for auger system using increasing airflow rates.	
Medium moisture content (63.8%), Quicklime dose = 10%.	71
Figure 4.31. Ammonia capture for the auger system using varied airflow rates.	
High moisture content (76.5%), Quicklime dose = 10%.	72
Figure 4.32. Temperature characteristics for auger using varied airflow rates. High	
moisture content (76.5%), Quicklime dose = 10%. T1-T3 represent	
temperatures from the three equally spaced thermocouples along the 4.57	
meter reactor.....	73

Figure 4.33. Temperature profile for auger using varied angles and speeds to vary mixing intensity. Medium moisture content (63.8%) air flow at 3 CFM, 10% Quicklime.75

Figure 4.34. Ammonia capture for the auger reactor varied angles and speeds of operation. Medium moisture content (63.8%) airflow at 3 cfm, 10% quicklime.76

Figure 4.35. Stabilization temperature profile for quicklime doses of 10% on a wet weight basis. Low moisture content = 51.6%, medium moisture content = 63.8%,77

Figure 4.36. Stabilization temperature profile for quicklime doses of 15% on a wet weight basis. Low moisture content = 51.6%, medium moisture content = 63.8%, high moisture content = 76.5%. T1, T2, and T3 represent temperatures at 5-foot intervals along the reactor.78

Figure 4.37. Stabilization temperature profile for quicklime doses of 20% on a wet weight basis. Low moisture content = 51.6%, medium moisture content = 63.8%, high moisture content = 76.5%. T1, T2, and T3 represent temperatures at 5-foot intervals along the reactor.78

Figure 4.38. Ammonia capture for the auger system using 10, 15, and 20% Quicklime Doses. Moisture contents of 51.6 %, 63.8 %, and 76.5 % are shown. Airflow was set at 4.25 liters / s.80

Figure 4.39. Temperature profile for auger using varied quicklime doses. High moisture content (76.5%), airflow set at 4.25 liters / s. T1, T2, and T3 represent temperatures at 5-foot intervals along the reactor.81

Figure 4.40. Temperature profile for auger using varied quicklime doses. Medium moisture content (63.8%) air flow at 3 CFM. T1, T2, and T3 represent temperatures at 5-foot intervals along the reactor.82

Figure 4.41. Temperature profile for auger using varied quicklime doses. Low moisture content (51.6%) airflow at 3 CFM. T1, T2, and T3 represent temperatures at 5-foot intervals along the reactor.82

Figure 4.42. Matching trials with and without insulation of the auger reactor using the medium moisture content (63.8%) manure at quicklime doses of 10, 15, 20%. T1, T2, and T3 represent temperatures at 5-foot intervals along the reactor. Dashed lines represent the results from the insulated trials.....84

Figure 4.43. Temperature profile for the insulated auger using a range of raw manure temperatures. Medium moisture content (63.8%) air flow at 3 CFM. T1, T2, and T3 represent temperatures at 5-foot intervals along the reactor. ..85

Figure 4.44. Percent of hydration accomplished per minute for a range of moisture contents screen against quicklime doses of 10, 15, and 20%.....89

Figure 4.45. pH profile as a function of quicklime dose for a 200 gallon ribbon mixer.90

Figure 4.46. Temperature profile as a function of quicklime dose for a 200-gallon ribbon mixer. Moisture Content = 75.6%.....91

1 Introduction

Flush systems used in commercial swine farming create a need for waste lagoons, which raise environmental concerns over spills and odors. Reduction of environmental hazards such as spills and excess nutrients on the farm may be achieved by immediate separation and partitioning of nutrients within excreted waste. Quick separation limits contact time between feces and urine. Likewise, contact between urease inherent in the feces and urea within the urine is reduced and conversion of urea to ammonia and carbon dioxide by fecal enzymes and microbes (Koger et al., 2001, Humenik et al., 2002) is therefore minimized.

Under-floor belt systems employ a slow moving conveyer that eliminates the need for flushing, and when operated at an angle, also facilitates a quick separation of liquids and solids (Koger et al. 2001). Belts were first used for this purpose in the poultry industry and different variations have been screened for their efficiencies (Sobel, 1977). The initial convex belt design used for swine waste separation was described by Elmer et al. (2001). A belt as described by Elmer et al. (2001) was constructed by FMC (Philadelphia, PA), and was installed September 30, 2002 at the North Carolina State University Lake Wheeler Swine Educational Facility, and pigs with an average weight of 29.5 kg were placed above it on October 7, 2002. On average the pigs gained 91 kg each in 95 days and were replaced with smaller pigs again on January 13, 2003. This belt was designed specifically as a platform for various utilization strategies of the solid and liquid streams resulting from the separation (Humenik et al., 2002).

Stabilization of raw manure solids is vital to avoid extreme anaerobic odors and pathogen promulgation. U.S. Environmental Protection Agency (EPA) issued new federal regulations for biosolids management in 1993 (CFR40 Part 503). Biosolids may be defined as sewage sludge generated from the treatment of domestic sewage. These regulations do not govern the treatment, storage, and application of manure solids, however these guidelines are used as benchmarks to judge the quality of stabilized manure solids in this work. The regulations define two classes of biosolids which may be applied to land, Classes B and A. "Class-B" biosolids are within the limits considered safe for land application, landscaping, and land reclamation. However Class-B biosolids must be managed and periodically monitored to ensure that trace metals and pathogens remain at safe levels due to the unstable nature of these solids.

Class-A designation is the highest quality identified for biosolids under the CFR regulations, and require compliance with strict treatment parameters to ensure safety for immediate public contact. Manure solids are not regulated under the CFR40 code, however for comparison it was determined if quicklime stabilization could be used to create a solids product meeting the same standards for Class-A biosolids. Requirements of the CFR for Class-A biosolids are

- reaction temperature $\geq 52^{\circ}\text{C}$ for 20 minutes.
- residual product pH of 12 for 2 hours and remain above 11.5 for the next 22 hours
- final solids content of at least 50% solids

1.1 Lime-Stabilization

The purpose of this research was to investigate the utility of quicklime (CaO) in creating a stabilized end product meeting the same standards of Class A biosolids as defined in the CFR40. The regulations specify several stabilization techniques, including alkaline stabilization. The use of quicklime to chemically stabilize biosolids from municipal waste systems has been demonstrated to be effective (Rogers and Cox, 1995, Wong and Fang, 2000). Typically pug mills are used to mix dewatered biosolids with granular quicklime for 15-30 minutes in an auger-type conveyance. During this stage of the hydration reaction, (Equation 1.1) the pH of the manure rises above 12 and heat is generated through the exothermic hydration reaction (Smith, 1998).



However lime stabilization of manure solids is not well understood. Quicklime hydration is an exothermic process with the potential to kill many pathogens by producing heat. However, the manure is made toxic to the microbes due to the alkaline conditions present during stabilization. The pH-induced stabilization effect is due to inactivation of bacteria and conversion of most metals into an insoluble alkaline form.

1.2 NH₃ Loss Through Volatilization During Stabilization

Ammonia volatilization is expected when a substance rich in ammonium (NH₄⁺) experiences a large increase in pH above the pKa (9.3 for NH₃). A pH of 12 is required for proper stabilization of municipal biosolids. Stabilization of raw manure is primarily expected to require a similarly high pH. At this pH, ammonia comprises the vast majority (>99%) of the total ammoniacal nitrogen, and therefore loss through

volatilization is substantially higher than that experienced at neutral pH values. The amount of ammonia lost is of concern for both environmental and economic reasons. Environmentally, ammonia volatilization is of concern for reasons associated with odor and respiratory health of swine and farm personnel. The Occupational Safety and Health Administration has set a limit of 25 parts per million (ppm) for farm personnel; likewise agricultural scientists in Europe of the COSHH (Control of Substances Hazardous to Health) have set the same limit for a ten minute exposure (Williams, 1992). Another detrimental affect of ammonia volatilization is the increase of pH in local rainwater, which allows more SO₂ to dissolve within it, eventually forming ammonium sulfate. Precipitation introduces the ammonium sulfate to the soil, which is then oxidized to nitric and sulfuric acid. Apsimon et al. (1987) demonstrated this essential role played by atmospheric ammonia in creation of acid rain.

Economic feasibility of utilizing the released ammonia depends on many factors. The rate at which the manure ammonia is liberated will affect both the methods of capture and potential for utilization. The faster that the ammonia becomes a gas, the smaller the treatment time for ammonia removal. As well, a smaller mixing/stripping time is required to capture ammonia when given off at a faster rate.

1.3 Objectives

- Determine product characteristics with respect to pH, temperature, pathogen indicators and moisture after mixing various doses of quicklime with separated manure having a range of moisture contents.
 - Estimate compatibility with meeting CFR40 Class A biosolids regulations.

- Determine initial ammonia volatilization rate as a result of various quicklime doses and initial moisture content.
 - Determine long term volatilization rates over an extended period of time.
- Determine and model the effect of quicklime dose, airflow rate, raw manure temperature, and moisture content on product temperature, moisture content, and ammonia volatilization for an experimental quicklime stabilization reactor.
- Develop a heat balance for a prototype reactor that can be used for the evaluation of optimum conditions to achieve desired hydration heat/reaction temperatures and allow for the adjustment of residual quicklime within the product.
 - Estimate compatibility with meeting CFR40 Class A biosolids regulations.

The primary goal of this work was to evaluate quicklime stabilization as a means of treating belt-separated manure to create a product meeting the same standards as a Class-A biosolids under the regulations defined in CFR40, Part 503. The initial goal was to characterize the manure to be stabilized in Part 2, with respect to pH, ammonia, and moisture content. Next 16-liter batch scale testes were conducted to determine the batch reaction temperature, reaction and residual pH, and moisture content for quicklime doses of 5 %, 10 %, and 15 % by wet weight for a range of manure moisture contents.

At a bench scale jar tests were conducted to determine the initial volatilization rate during mixing for different quicklime doses. Longer observation periods were required to find the volatilization from stored product over an extended period of time until approximately 90% of the original ammonia was lost. An auger reactor simulating a full-scale on-farm system was constructed to study a range of manure moistures under a wide variety of conditions such as temperature, airflow for ammonia capture, and

quicklime dosage by heat balance around the reactor. Finally, a statistical analysis performed on the independent and monitored variables and stepwise elimination of independent variables was conducted to determine which exhibit a significant effect on the product classification, temperature, moisture content, and ammonia volatilization. Recommendations on which operational parameters were most beneficial to product classification benchmarks were made for use in designing full-scale treatment systems.

2 Literature Review

Disposal of swine waste is perhaps the single largest area of conflict between industrial farmers and environmentalists. Minimization of environmental hazards such as spills may be achieved by immediate separation and partitioning of nutrients within excreted waste. However, stabilization of raw solids is vital to avoid extreme anaerobic odors and pathogen promulgation. These areas must be properly addressed in order to prevent premature exclusion of innovative alternatives. It has been suggested that nutrients found in swine waste have an economic value (e.g. Stonehouse and Narayanan, 1984, Honeyman, 1996). Alternatively, others have decided that these nutrients are not worth the trouble of management for reuse and should be disposed with the least expensive method available (Schnitkey and Miranda, 1993). Low cost modification of existing waste treatment systems to change waste into a viable product is preferential to destroying the increasingly small profit margin of swine/animal farmers in the process.

The accumulation of nutrients can become a liability if not processed and utilized in a timely and safe manner. Nitrogen is readily utilized and expended through cropping, however phosphorus can gradually build up in soils to levels presenting environmental hazards through run-off and leaching into soils. Partitioning of nitrogen and phosphorus into solid and liquid streams would be useful in many ways. The separated solid manure, concentrated in phosphorus, can be exported farther away from the production area to locations which are phosphorus deficient, with smaller risk to the environment. The liquid stream, having a proportionately larger concentration with respect to phosphorus, can be applied locally with greater flexibility in use. The nitrogen content of the two streams is similar, however a greater concentration of nitrogen can be found in the solid

stream as belt speed is increased due to the retention of a larger portion of the liquid waste.

2.1 Separation by belt systems

Methods of separation based on gravity are generally less intensive and less expensive to operate than mechanical separation schemes. Belt systems are one of the more efficient mechanical systems for separation of swine waste. Belt processes can take many forms such as simple conveyers to complex presses. Conveyers are merely belts used to transport waste from one location to another. Presses are usually complex systems of compression rollers, which serve to squeeze the water through the fabric of the belt for the purpose of dewatering. Other belt systems utilize gravity to perform initial separation through liquid run-off accompanied by scrapers to remove solids. These hybrid systems employ a slowly moving under-house conveyer belt to eliminate the need for flushing therefore reducing the total volume of waste to be treated. These types of processes also have the benefit of immediate solid-liquid separation, minimizing the conversion of urea to ammonia and carbon dioxide by fecal enzymes and microbes (Koger et al., 2001).

In a similar study solids removed were dried to 20-50% moisture. These solids (excrement) spent an average three-day residence time on a belt under the slotted floors (Kaspers, 2001). Solid manure production from this type of operation is expected to yield 280 kg of solid waste at 70 % moisture / pig space / year. Similarly, liquid from this type of system is assumed to be produced at 884 l / pig space / year (Bottcher et al., 2001).

2.2 Solid Product Classification (Class-B versus Class-A)

In 1993 the U.S. Environmental Protection Agency (EPA) issued new federal regulations for biosolids management. These regulations were issued after extensive studies of biosolids application to protect humans, plants and animals. The EPA and the Washington State Department of Ecology placed regulations on the acceptable levels of pathogens and trace metals found in biosolids. The regulations define two classes of biosolids, which may be land applied. "Class-B" biosolids are within the limits considered safe for land application, landscaping, and land reclamation. Class-B biosolids must however be managed and periodically monitored to insure trace metals and pathogens are at safe levels due to unstable nature of these solids. For this reason, public access to/on Class B land application sites is restricted for one to twelve months after application.

The EPA Part 503 Biosolids Rule, September 1994 (EPA/8332/R-93/003) sets forth parameters for class determination, which include:

Concentration of metals (arsenic, cadmium, chromium, copper, lead, mercury, molybdenum, nickel, selenium, and zinc). These limits apply to both Class A and B solids as metals are non-degradable. Defined - (40 CFR 503.13(b)(3)). Table 2.1 below illustrates the ceiling limits on metals for Class-A biosolids under the CFR40 guidelines.

Table 2.1 MCL for Class-A solids defined under the CFR40.

Metal	Ceiling limit for land application (mg/kg)	Ceiling limit for lawn and garden application (mg/kg)
Arsenic	75	41
Cadmium	85	39
Copper	4300	1500
Lead	840	300
Mercury	57	17
Molybdenum	75	N/A
Nickel	420	420
Selenium	100	100
Zinc	7500	2800

Activity of pathogens (bacteria, viruses, and parasites) Processes meeting either of the limits below are acceptable.

Table 2.2. Pathogen ceiling limits for Class-A and Class-B biosolids.

Class	<i>Fecal coliform</i>	<i>Salmonella sp.</i>
A	<3 / 4 grams dry solids	<2,000,000 / gram dry solids
B	<1000 / 1 gram dry solids	N/A

Class-A designation is the highest quality identified for biosolids under the CFR regulations, where more stringent limits are met to ensure safety for immediate public contact. Processes to Further Reduce Pathogens (PFRP's) (for Class-A solids) are used to decrease microbial content to levels below those achieved through Processes to Significantly Reduce Pathogens (PSRP) for Class-B solids. Acceptable processes are defined under the 40 CFR 503.32(a), for Class-A solids production and 40 CFR 503.32(b) for Class-B solids production. Class-A biosolids may be used in almost any setting, including commercial agriculture, home lawns, and gardens. They can also be

used in place of certain commercial fertilizers, Calcium rich topsoil, or composted soil amendments. Class-A solids are preferential to Class-B biosolids because:

- Less Restrictions for Use (such as land application)
- Reduced Costs of Solid Management (less bureaucracy)
- Preferred by end users (Minimized Risk for Public Health)

Listed below are several alternatives recommended for achieving Class-A pathogen levels.

2.2.1 Summary of Four Alternatives for Meeting Class A Pathogen Requirements

- Thermal treatment (One of four temperature-time regimens dependent on the heating method and percent solids)
- High pH and high temperature treatment (pH, temperature, and drying requirements must be met)
- Undefined process treatment (demonstrated reduction of enteric viruses, and viable *helminth ova salmonella* sp. or fecal *coliform*)
- Treatment by PFRP (processes such as UV radiation to further reduce pathogens)

The second alternative listed above is most fitting to the lime-stabilization method. The pH requirement (pH>12 for 72 hours) is met simply by sufficient lime addition. The temperature must also be raised to greater than 52°C for 12 hours or longer during this 72 hour period. Afterwards, the solids content of the product must be raised to at least 50 % by air-drying. (40 CFR 503.32/a/4/ii/A-C) For solids with less than 93 %

moisture, the requirements for time and temperature are defined in 40 CFR 503.32 by the following equation:

$$D = \frac{131,700,000}{10^{0.1400T}}$$

Where **D** is time in days and **T** is temperature in degrees Celsius. After treatment, the solids content of the product must be raised to at least 50 % by air-drying. (40 CFR 503.32/a/4/ii/A-C).

2.3 Vectors

The pathogens in biosolids pose a disease risk when they are brought into contact with susceptible hosts (plant or animal). Vectors, which include flies, mosquitoes, fleas, rodents, and birds, can transmit pathogens to humans physically or through playing a specific role in the life cycle of a specific pathogen. Reducing the attractiveness of processed solids to vectors reduces the potential for transmitting diseases. The Part 503 rule contains 12 options, which are summarized below, for demonstrating reduced vector attraction for biosolids. These requirements are designed to reduce the attractiveness of biosolids to vectors or prevent vectors from coming in contact with the biosolids. One of the first eight requirements must be met in order to legally apply/sell/give any biosolid product for agriculture, public land applications, or site reclamations. Similarly, one of the requirements listed as 9-12 must also be met to create such a product from raw septage.

2.3.1 Summary of Options for Meeting Vector Attraction Reduction

- 1 Meet 38% reduction in volatile solids
- 2 Demonstrate vector attraction reduction with additional anaerobic digestion in a bench scale unit
- 3 Demonstrate vector attraction reduction with additional aerobic digestion in a bench scale unit
- 4 Meet a specific oxygen uptake rate for aerobically digested biosolids
- 5 Use aerobic process at $>40^{\circ}\text{C}$ for 14 days or longer
- 6 Alkali addition under specified conditions (pH 12 or higher for 2 hours without additional alkaline)
- 7 Dry biosolids with no unstabilized solids to at least 75 % solids
- 8 Dry biosolids with unstabilized solids to at least 90 % solids
- 9 Biosolids shall be injected below the land surface
- 10 Incorporate biosolids into the soil within 6 hours of application to or placement on the land
- 11 Cover biosolids at the end of each days operation
- 12 Alkaline treatment of domestic septage to pH 12 or above for at least 30 minutes without the addition of more alkaline material and remain above 11.5 for an additional 22 hours

2.4 Solid Product Development

Raw waste and processed agricultural waste have different physical and chemical compositions (Duffera et al., 1999, Hill and Tollner, 1980). Drying of solids within the

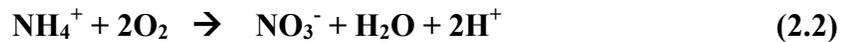
waste fixes a certain portion of ammonia and phosphorus, which serves to reduce nutrient loss through leaching. These solids may be used offsite in areas too far away to be irrigated and too small to warrant their own irrigation systems. Composting with a bulking agent allows for the creation of a humus by product and reduction of offensive odors through biological stabilization. However, biological stabilization is slow, non-continuous, and relatively intensive if active aeration is used. If performed on the ground, composting has the potential for significant nutrient leaching when environmental forces such as rain create appropriate conditions. Other alternate treatments for separated solids are needed to efficiently and safely create a stable product of significant value. Simultaneously, a liability (solid waste) will be eliminated.

2.4.1 Lime Stabilization

Option twelve of the vector reduction summaries allows for alkaline stabilization. The use of lime to chemically stabilize biosolids from municipal waste systems has been demonstrated to be effective (Wong and Fang, 2000). However lime stabilization of raw solids is not well understood. The pH-induced stabilization effect is due to inactivity on the part of bacteria and locking of most metals into an insoluble alkaline precipitate. While liming is an exothermic process, microbes are neutralized by the alkaline conditions. The resilience of microbes to a particular process is an important factor, as this will determine the ability of the process to create a long-term stable solid. The agricultural value and compatibility of a lime-stabilized solid product with current swine operations is the direction for further studies.

2.4.2 Acidification

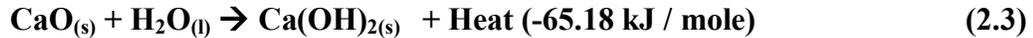
Alkaline liming additions to slightly acidic soils are welcomed so long as the soil pH change does not make metals too unavailable for plant uptake. Continuous addition of ammoniacal nitrogen gradually increases the acidity of the soils through Reactions 2.1 and 2.2 below:



Reaction 2.1 shows the conversion of ammonia to the ammonium ion, which is biologically utilized to form a nitrate ion in Reaction 2.2. Assuming an application rate of 50-200 kg N / ha, acidification (creation of H^+) by this mechanism is 4-16 times the rate due to acid rain in heavily industrialized areas (Sumner, 1991). Soils, which are limed periodically, are immune to this type of acidification due to the increase in buffering capacity. It is, however, difficult to raise soil pH above 6.5 in areas where variable charged particles such as oxide minerals are abundant. These soils are significantly resistant to pH changes because they contain particles with hydroxylated surfaces, in which H^+ ions can be released to counter OH^- ions. As equilibrium shifts the counter ions form water and reestablish a pH near the original value.

2.4.3 Exothermicity

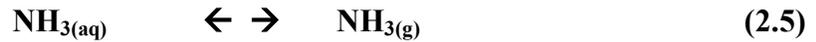
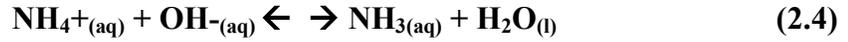
Lime solubility with water is approximately 1 g / L at 25°C and atmospheric pressure. Generally, quicklime (calcium oxide) addition to water can be described by Reaction 2.3 below.



This is an exothermic reaction as indicated by the negative value of the reaction heat ($\Delta H_{\text{rxn}} < 0$). The exact degree that this reaction will be completed (% moisture used in hydration of quicklime) when quicklime is added to raw waste remains unknown, however it may be gauged somewhat by the amount of heat generated during the initial lime addition. Measurement of the exothermicity of the lime-stabilization process is desired in order to determine if enough heat is generated to raise temperature to a value sufficient to qualify as a Class-A solids treatment (>52°C for 12 hours) technique or possibly warrant alternate uses for this energy.

2.4.4 Volatilization of NH₃ During Stabilization

Ammonia volatilization may be significant for the stabilization process. Ammonia volatilization is to be expected when a substance rich in ammonium experiences a large increase in pH. Prediction of volatilization rates during stabilization can lead to strategies to capture and utilize the commodity with efficiency. The pKa for NH₃ is 9.3, meaning at 25°C and a pH of 9.3 equal amounts of dissolved NH₃ and NH₄⁺ should be present at equilibrium. As the pH is raised above 9.3 equilibrium of Reaction 2.4 shifts right.



Likewise, as the amount of aqueous ammonia increases Reaction 2.5 seeks to reach its own equilibrium through volatilization. The pH for proper stabilization of municipal biosolids is generally a least 12. Stabilization of raw manure is expected to be at a similar high pH. At this high pH, ammonia composes the vast majority (>99 %) of the total ammonical nitrogen, and therefore loss through volatilization is substantially higher. The exact amount and rate of ammonia lost are a focus of this work.

3 MATERIALS AND METHODS

3.1 PART 1 - Characterization

Characterization of manure used in testing is required to determine a baseline value for the average raw physical and chemical characteristics. To characterize raw manure, used during Part 2 – Mixing and Volatilization, 12 samples were taken from swine units at the North Carolina State University Lake Wheeler Road Field Laboratory Swine Education Unit over a two-week period. Manure from a belt system was not available for the initial experiments with quicklime, as construction of a belt system was still in the drawing and manufacturing stage. Freshly scraped manure was therefore used for a solids characterization and fundamental experiments concerning the reaction's degree exothermicity and quality of the treated and stored manure. This characterization also demonstrates the capacity of quicklime to treat manure separated by large-scale screening. Raw manure failing to fall to a flush pit was scraped, mixed, and sampled three times per week. Moisture, ammonia, pH, and phosphorus available through a weak acid extraction were measured for each of the samples.

3.2 PART 2 - Mixing and Long Term Storage

The relationship between quicklime dose, manure moisture content, and product stability was determined to give insights that would allow narrowing the range of doses tested in Part 3 to follow. Testing was performed at a scale of approximately 3.5 gallons of manure per batch. Quicklime doses of 5 %, 10 %, and 15 % were evaluated. This was

done to provide data for the comparison to the CFR40 guideline for a Class-A biosolids product (See Literature Review – Class-A Biosolids).

Manure was collected from the same swine units used in Part 1 daily at 9:00 AM and taken to a secluded area for treatment and storage. Raw manure was taken for analysis after mixing each 16-liter batch prior to quicklime addition. Quicklime was added and mixing was continued. Temperature and pH were monitored at two minute intervals during mixing, until temperature reached a maximum value; then every two minutes until at least 40 minutes had elapsed from the initial point of mixing. Afterward, pH and temperature were measured every 12 hours for a 72-hour period. Samples were taken from the stabilized product and at 1-week intervals for 4 weeks. The nutrient analysis was performed after stabilization and during storage to determine loss and availability.

The pH of a lime-stabilized product will decrease during storage as solids come in contact with atmospheric CO₂ and hydrated lime is converted to calcium carbonate (Smith et. al, 1998). Microbial populations will rise as pH declines and the manure becomes more suitable for re-population. Measurement of the residual product pH during storage will give insight into the allowable storage time corresponding to different lime concentrations used in treatment.

The temperature and pH resulting from the liming process are thought to be sufficient to eliminate the majority of pathogens. However, product verification would be lacking without proof to establish this outcome. Therefore, enumeration of *E. coli*, and coliform were done weekly to give an indication of the presence/concentration of fecal coliform within the raw solid and finished product to demonstrate pathogen

elimination, regrowth, and safety associated with differing doses of quicklime over a range of moisture contents. Standard methods were followed (Clesceri et. al, 2000, Csuro and Csuro, 1999)

for the calculation of the MPN for each of the samples with regard to E. coli and fecal coliform indicators.

The experimental procedure for Part 2 was as follows. Raw manure was collected, weighed, and placed in mixing container. Temperature and pH were recorded and mixing initiated. After 4 minutes mixing solids appeared homogeneous. Samples of the raw manure were taken for microbial analysis of pathogen indicators and temperature was measured. Quicklime was added at the appropriate dose for the given test (5 % - 15 %). Temperature and pH were measured at two minute intervals. Mixing was ended when temperature increase was $< 0.5^{\circ}\text{C}$ for a two minute interval (T_{final}). Temperature and pH were monitored for a period of 40 minutes. Stabilized solids were then stored in 22-liter plastic bins on site for further measurements. Temperature and pH were measured for the stored product at 12 hour intervals for 72 hours and samples were taken weekly for eight weeks to determine microbial regrowth and pH decline.

Clean 20-liter plastic buckets were used for the mixing vessel. A double-helical, five inch (12.57 cm) diameter drywall blade powered by a ½ inch industrial strength multi-speed drill was used for mixing. Hanging scales with a 20-kg capacity were used for weighing manure and hanging scales with a five-kg capacity were used for weighing granular quicklime, which was crushed to a powder before addition to manure. The mixing vessel was held or fastened securely during mixing as the unexpected viscosity increase of the manure can and has caused some rather frustrating and messy accidents.

The basic analysis for raw manure and samples taken throughout Part 2 of this work included ammoniacal nitrogen, available phosphorus (through a Mehlich III weak acid extraction), total carbon and nitrogen, as well as total coliform and *E. coli*.

3.3 Part 3 - Bench Scale Analysis of Initial Ammonia Volatilization

Belt separated solids became available for Part 3 of this work. The consistency and viscosity appeared very similar to the scraped manure used in Parts 1 and 2 upon visual inspection. The objective of Part 3 was to develop a volatilization profile for NH_3 during mixing after quicklime addition. Doses of 5 % and 10 % quicklime were chosen for examination in Part 3. Quicklime doses of 5 % were excluded from Part 3 due to a low temperature response and lessened pathogen kill as observed in Part 2 for this dose. The Results and Discussion section give more detail on this reasoning. Data for the raw manure in this section was also intended to provide a base for comparison of certain characteristics of the belt-separated manure and the scraped manure.

A small scale mixing apparatus was constructed from a kitchen style hand blender. The blender was attachable to a one-liter mixing container and made airtight. Two gas ports were added, allowing inlet and outlet flow. A schematic of the experimental setup is shown in Figure 3.1. After addition of manure, quicklime, and mixing blade apparatus, the air flow was run at three liters per minute providing approximately six air changes per minute.

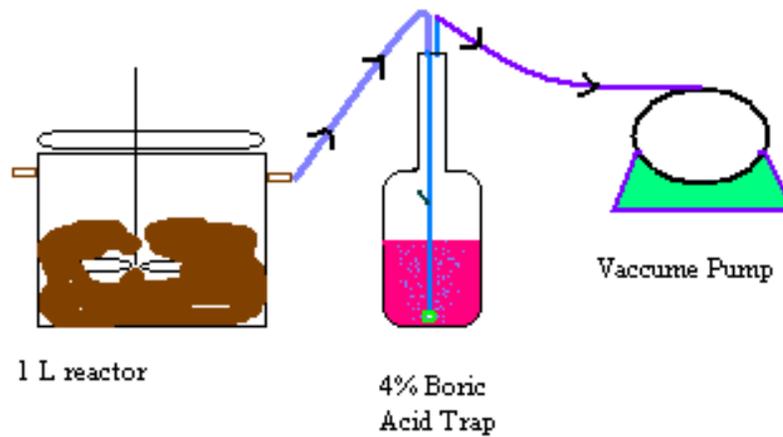


Figure 3.1. Schematic of mixing and sampling apparatus for Part 3 including acid traps.

Granular quicklime was used starting with these experiments to compare mixing compatibility with the smaller mixing apparatus. Packing of manure in the reactor is a learned skill in that poor loading resulted in poor mixing during preliminary experimentation. Conversely, tight packing eventually resulted in motor stress for the mixer. The quicklime mixed with manure becomes increasingly viscous after a maximum temperature is reached, and this can result in a burnt out motor for the hand mixer.

Acid traps were employed, using 100 mL of a 4 % boric acid (H_3BO_3) solution, to capture ammonia liberated from the manure by simple diffusion. Vacuum pumps were used to draw air through one inlet across the mixing manure and through the acid trap(s). Air diffusers were used in the traps to increase the surface area to volume ratio for the ammonia-laden air. Initially, traps were placed in series to gauge the trapping effectiveness of the first trap by catching ammonia that escaped the first of the boric acid solutions without being adsorbed. Traps were changed every ten minutes during mixing for the quicklime treated manure.

Initially, air was drawn through the apparatus at a measured rate of 3 liters per minute for 20 minutes to determine if the atmospheric contribution of ammonia was significant. Next, air was drawn across manure without quicklime addition and samples were taken at the same rate in order to determine the background volatilization of ammonia from non-treated manure. This was essentially a 0 % lime treatment that was processed in the same manner as the other treatments.

Duplicates were performed with the same manure for 10 % and 15 % quicklime doses for reproducibility. Also, the same batch of manure was used for doses of 10 % and 15 % to show the dosage effect on manure with identical characteristics. Analysis for Part 3 initially included total phosphorus and nitrate for completeness of the analysis. These data may be useful when trying to draw conclusions about the fate of individual nitrogen species with the manure and stabilized product.

3.4 PART 4 - Mass Balances for Volatilized Ammonia

Ammonia volatilization was significant throughout the 60 minute period monitored in Part 3. Volatilization profiles for extended periods of time were needed in order to ascertain the approximate time required for liberation of the majority of ammoniacal nitrogen. Volatilization rates were determined by examination of off-gas for longer time periods (one month) as the previous study proved to be too brief for complete capture of NH_3 . Specific time periods and intervals were tested as shown in Table 3.1. Mass balances will show total nitrogen loss as NH_3 during stabilization, however, to verify this balance the volatilized nitrogen must be captured and quantified.

Boric acid traps were again used to quantify ammonia loss by diffusing off-gas from the stabilization reactor. Inlet air to the reactor was filtered through an acid trap to eliminate the continuous addition of atmospheric ammonia to the trap. Comparison was made with the total ammonia captured and the mass balance on the solids concentration of ammoniacal nitrogen before and after the stabilization and sampling period. Likewise, these values were compared to those predicted by the equilibrium equation for the solids at the given temperature, pH, and ammoniacal nitrogen concentrations. Analysis of moisture in the raw solids and stabilized product was conducted to convert volatilization data to a mass scale for determination of the per gram solids rate used in the analysis of ammonia. Frequency for changing and sampling the acid traps used to capture ammonia from the stabilized product is shown below in Table 3.1.

Table 3.1. Sampling frequency for acid traps used in Part 3.

Sampling Frequency	# of Samples	Total Time
30 min	4	2 hours
1 hour	4	4 hours
6 hours	3	18 hours
12 hours	6	3 days
24 hours	24	24 days
Total →		28 days

As ammonia was liberated, the volatilization slowed, allowing for a decrease in acid trap sampling frequency. The resolution needed to evaluate data trends was satisfied by decreasing the sampling frequency gradually. The data provided a smooth and complete profile for long term ammonia volatilization rates from the stabilized manure.

3.5 PART 5 – Steady State Auger System Analysis

A mathematical model for the hydration of quicklime by mixing with belt separated swine manure would be especially useful in the design of systems aimed at treatment on a commercial scale. An auger is a viable mixing device for on-farm operations. By knowing approximate concentrations of ammonia, optimal treatment residence times, auger speeds, manure loading rates, and matching effective quicklime doses, commercial implementation of this stabilization technique is more probable. Residence time refers to the average amount of time that the components of manure and quicklime spend in the auger reactor. Average residence times were calculated by determining the amount of time required to elute one-half of a slug of manure added to the system. This was measured on a mass basis by pre-measuring the slug and placing the balance and receiving vessel under the ejection end of the reactor. A simple schematic of the reactor is shown below (Figure 3.2).

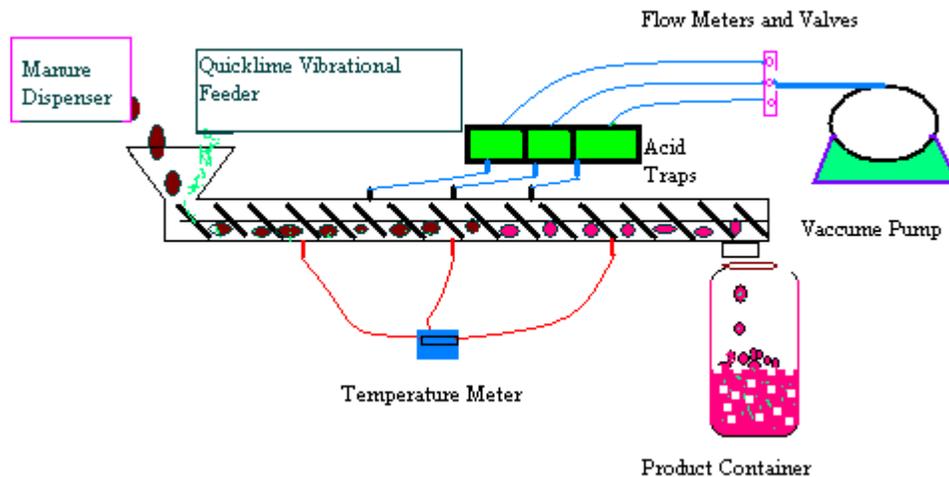


Figure 3.2. Schematic of auger reactor

A steady state system is generally lower maintenance than a batch process, unless an intricate system of timers and automations are employed in the latter making the batch operations costly and more technically involved. A simple continuous system capable of operating at a range of conditions with respect to temperature, mass flow, mixing intensity and gas flow rates would be indispensable for estimation of the effects of the process variables described above.

A steady state system was capable of processing approximately 20 - 40 kg of manure per hour was proposed, designed, and built. This system is capable of handling the waste from a 5 pen - 15 hog system in less than an hour per day. The auger was composed of a 14 degree pitch iron screw wrapped around a 2.54 cm rod (1 inch), matched to a 15.24 cm (6 inch) ID iron pipe whose thickness was 0.24 cm (0.6 inch) made by Westfield® (Rosemort) (UT-1-01). The auger was then fitted with a Delta

VFD-B AC (Thirsk) motor drive with optional jog functions. Gas ports were added along the top of the shaft for removal and sampling of volatilized ammonia and equipped with flow meters, acid traps and vacuum system. To continuously monitor temperature, thermocouples were added at three equidistant points using compression fittings, specially designed probes, and an OMEGA HH501DK Digital Thermometer (Stanford).

The auger was assembled, housed, and operated in the Research and Demonstration Building at the North Carolina State University Lake Wheeler Road Field Laboratory Swine Education Unit. A set of chains was used to suspend the discharge and drive end of the auger to create an incline for more robust mixing. The auger speed could then be increased to create greater mixing intensities while leaving the residence time unchanged for different angles of operation. Other properties such as moisture, temperature, and flow rate are likely to influence the average residence time. However, these factors were not examined with respect to residence time in combination with angles of operation. Insulation was later added to better gauge heat loss and observe the reaction at higher temperatures.

A vibrational bean counter was converted into a quicklime dispenser by the addition of a sealable hopper. Problems were encountered with the powdered quicklime settling to a semisolid layer near the metal slide discharge. This was overcome by a few coats of appliance-grade epoxy spray paint. Both granular and powdered quicklime were screened for compatibility with the vibrational feeder and auger. The smallest available granule, termed fines, was used based on its price, stability, and functionality in the feeder.

A screw-type auger dispenser, four feet in length, performed manure addition to the auger. The manure dispenser hopper was a stainless steel 644 liter (170 gallon) trough, approximately 36 cm by 100 cm (14.2 inch by 39.4 inch) at the top, equipped with an agitator and hinged lid. Initially the dispenser's discharge was in spurts through the 7.62 cm by 12.70 cm (3 inch by 5 inch) downspout, resulting in visibly poor mixing and auger clogging. This unmoderated flow rate was also far beyond that of the quicklime dispenser's range of 10 to 20 % doses. A constant stream of manure was produced by manufacturing a series of nozzle-plates, which varied in the number of holes and size. At the average moisture content to be tested (65 %), a series of trials was conducted with the dispenser to pick the nozzle with the most consistent flow, at a range to match the flow capacity and range of the vibrational feeder.

After completing the midrange moisture manure trials, the belt was run continuously to give the high-end moisture content of 76 %. This was below the desired moisture of 80 %. However, it was the highest moisture content that could be achieved without modifying the existing belt or adding water. Low-end moisture values of 52 % were achieved through intermittent operation of the belt once every 24 hours and slow drying by spreading out in a thin layer for eight hours in a dry environment before use.

3.5.1 Heat Balance

A heat balance was conducted to determine the amount of hydration heat released by the quicklime under the variety of conditions tested. The amount of heat added to the system through hydration and mixing must equal the amount lost through sinks such as changes in material temperatures, loss through natural convection, and

volatilization. The change in temperature of the components may be used to calculate a net loss of heat from the system in the case where temperature is increased. Basically, the heat balance takes the form of Equation 3.1, where the unknown is the heat generated through hydration.

$$0 = \text{Material Heat In} - \text{Material Heat Out} + \text{Heat Generated} - \text{Convective Heat Lost} \quad (3.1)$$

A schematic of possible heat sinks and sources for the auger reactor is shown below in Figure 3.3.

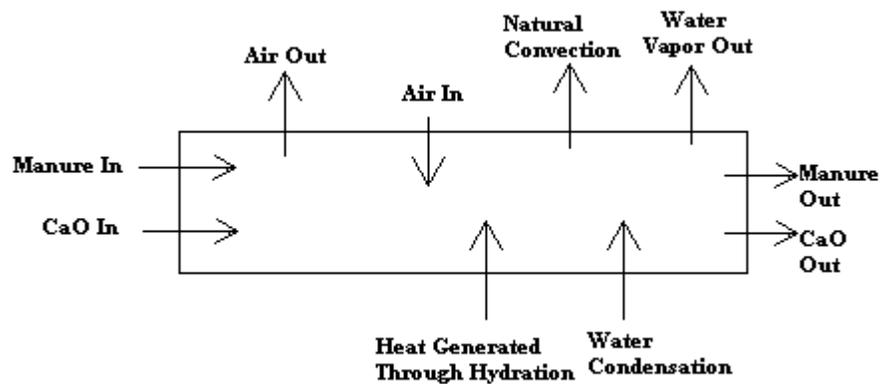


Figure 3.3. Schematic of heat sinks and sources for the auger reactor.

The heat balance around the reactor was performed under steady state conditions by accounting for the rise in manure and air temperature, the convective loss to the environment, the amount of heat required to volatilize captured ammonia, and the required heat of hydration to generate the total amount of heat observed. Volatilization of water was calculated from the flow rates and moisture contents of the manure and product. Heat addition solely through mixing was determined by auger operation without

the addition of quicklime. Convective heat loss was calculated by a thermodynamic model for loss from a horizontal pipe, where the exterior surface temperature, ambient temperature, and the external surface area are combined to give an effective rate of natural convection for the auger reactor for a particular trial (Geankoplis, 1993).

By totaling the heat sinks of volatilization, convection, and component temperature increases, an amount of heat is determined which is required to be fulfilled by the heat sources of hydration and mixing. If the heat added through mixing is neglected, hydration heat is therefore equal in magnitude but opposite in sign to the total of the heat sinks shown in parentheses (Equation 3.2).

$$0 = \Delta H_{\text{hydration}} + \Delta H_{\text{Condensation}} - (\Delta H_{\text{convection}} + \Delta H_{\text{volatilization H}_2\text{O}} + \Delta H_{\text{volatilization NH}_3} + \Delta H_{\text{manure}} + \Delta H_{\text{CaO}} + \Delta H_{\text{air}}) \quad 3.2$$

The amount of heat lost through phase change of NH_3 from a liquid to a vapor and the amount gained by the addition of mechanical mixing were insignificant to the overall balance (see the Appendix Part 5 page 137 - 138 for sample calculations). Sinks for the heat were obviously the convective loss and the amount required to raise the temperature of the manure and air. Heat capacities (C_{p_x}) for calcium oxide and air were average values for the temperature range, $0.65 \text{ J / g } ^\circ\text{C}$ and $1.13 \text{ J / g } ^\circ\text{C}$ (Perry and Green, 1995) respectively. These were used to determine the change in heat for calcium oxide and air (ΔH_{CaO} and ΔH_{air}) using Equation 3.3. Temperature change is expressed as a function of the reactor length. T1 and T3 are used to get an estimate of temperature change for two-thirds of the total reactor length and finally normalized to estimate the temperature change for the entire length of the reactor ($T_{\text{in}} - T_{\text{out}}$). Mass flow (MF) for each component was used to set all heat sinks as a function of time.

$$\Delta H_x = (MF_x) C_{p_x} (T_{in} - T_{out}) \quad 3.3$$

Thermodynamic data for the heat capacity of air, water, and quicklime are available in Perry's Handbook, however the heat capacity for manure or any biosolids may be defined by the weighted equation (Equation 3.4) based on the volumetric fractions of the mineral (f_m), water (f_w), organic components (f_o) (Hillel, 1980). These constants

$$C_{p_{Manure}} = C_{p_m} (f_m) + C_{p_w} (f_w) + C_{p_o} (f_o) \quad 3.4$$

The amount of heat required for volatilization ($H_{volatilization\ x}$) of ammonia or water is the product of the ammonia captured as a function of time (MF) or moisture lost and the heat of volatilization ($H_{volatilization\ x}$) for the given species ($H_{volatilization\ NH_3} = -33.4 \text{ kJ / Mol NH}_3$, $H_{volatilization\ H_2O} = -4.66 \text{ kJ / Mol H}_2\text{O}$) (Perry and Green, 1995). Equation 3.5 represents the heat required to volatilize ammonia or water as a function of time.

$$\Delta H_{volatilization\ x} = MF (H_{volatilization\ x}) \quad 3.5$$

Alternatively, condensation is opposite but equal in magnitude for phase change from a gas to a liquid. Therefore, the same equation applies with a change in sign for water which is absorbed as condensation for the product within the reactor ($\Delta H_{condensation}$).

The convective loss from a horizontal cylinder can be calculated for the exterior pipe temperature, pipe diameter (D), length (L), exterior surface area (2.19 m^2 for the auger reactor or $L \pi D$), and ambient temperature (Geankoplis, 1993). Equation 3.6 is modified, where the Geankoplis equation is multiplied by the surface area of the reactor, resulting in a total heat loss by natural convection for the prototype reactor.

$$\Delta H_{Convection} = 1.32 L (\pi D) ((T_{pipe} - T_{ambient}) / D)^{0.25} \quad 3.6$$

After determination of the quantity of heat lost through the sinks, the value may then be divided by the molar heat of hydration for calcium oxide (-65.18 kJ / mol) (Perry and Green, 1995) and multiplied by the residence time for that trial to determine the amount of calcium oxide hydrated for a given test. This will allow for the prediction of stabilization reaction temperatures and residual concentration in the product. This will be beneficial not only from a materials standpoint but also allows the option to leave a quicklime concentration desired for agricultural liming with the stabilized product.

The amount of calcium oxide hydrated divided by the amount added gives a hydration efficiency. The hydration efficiency is useful from two perspectives. In the minimal dose case, the lowest dose which achieves the Class-A temperature requirements may be estimated. Alternatively, the amount of quicklime added to leave a certain residual may be estimated. This would be useful to match residual pH and storage time required for a particular farm or operation. It is likely that the amount of calcium oxide hydrated as a function of time will be more useful to future design, as the totals for the reactor trials will change as the geometry and dynamics of the system are altered.

Table 3.2. Defined variables for heat balance.

Variable	Units	Definition
PSRP		Process to significantly reduce pathogens
PFRP		Process to further reduce pathogens
$\Delta H_{\text{Hydration}}$	J/s	Heat of hydration for CaO
$\Delta H_{\text{Condensation}}$	J/s	Heat of condensation for H₂O
$\Delta H_{\text{Volatilization } x}$	J/s	Heat of volatilization for component x (H₂O or NH₃)
ΔH_{manure}	J/s	Change in heat for manure
ΔH_{CaO}	J/s	Change in Heat for CaO
ΔH_{air}	J/s	Change in heat for air
$\Delta H_{\text{Volatilization } x}$	(J/mol)/ s	Heat of volatilization for component x (H₂O or NH₃) per mol
MF	g/s	Mass flow (Manure, CaO, H₂O)
f_m		Volumetric fraction for mineral component
f_w		Volumetric fraction for water component
f_o		Volumetric fraction for organic component
C_{p_x}	J / K	Heat Capacity for Component x (H₂O, Manure, air)
L	m	Pipe length
D	m	Pipe diameter (outside)
r	m	Pipe radius (outside)
T_{in}	K	Air temperature in
T_{out}	K	Air Temperature out
T_{pipe}	K	Average external pipe temperature
T_{ambient}	K	Average ambient air temperature

3.5.2 Statistical Analysis

Multiple linear regression was used to determine which of the independent variables had a significant effect on the dependent variables described in the SAS Section of Part 4.5.14 (SAS (r) Proprietary Software Release 8.2 (TS2M0) licensed to North Carolina State University-CAMPUSWIDE-T/R Copyright (c) 1999-2001 by SAS Institute Inc., Cary, NC, USA). Independent variables included manure moisture, quicklime dose, and manure and air flow rates. The sessions were executed on the WIN_PRO platform and elimination of independent variables was executed in stepwise fashion. Elimination of independent variables was according to the highest Pr>t: value (the indicator for significance in the SAS analysis) until all values for independent

variables fell below 0.2000, the benchmark indicating significance for the remaining variables.

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4 RESULTS AND DISCUSSION

4.1 Part 1 - Classification of Scraped Solids

Selected characteristics for the scraped, belt-separated, and screened (Hill and Baier, 2000) manure used in this research are shown in Table 4.1

Table 4.1. Average scraped and belt-separated manure parameters.

	Units	Screened	Belt solids	Scraped
NH ₃ -N	ug/g	963	2760	1318
Available Phosphorus	ug/g	NA	2610	2636
pH		8.3	6.8	7.5
Moisture Content	%	76	65	70
Carbon	%	10.2	17	11.5
Nitrogen	%	1.3	1.6	1

The results for ammonia and available phosphorus were slightly higher (10 %) than those reported by Westerman and Biscudo (2000), for screen separated flushed swine waste. Due to the fact that the removal, separation method and residence time were different for the characterization work here and the Westerman study slight differences are anticipated. Moisture, pH, and carbon to nitrogen ratio (C/N) were within the reported range. The difference in NH₃ may be due to increased volatilization prior to sampling for the higher pH solids.

Moisture values were greater than those reported by Koger et al. (2001) for separated belt manure. Approximately the same carbon content was found on a dry weight basis.

4.2 Part 2 - Long Term Mixing and Storage Testing

4.2.1 Mixing Temperature Profile

Scraped swine manure with moisture values of 68 %, 70 %, and 72 % were treated with quicklime doses of 5 %, 10 %, and 15 % by wet weight. The initial temperature profile with respect to time shows a distinct regime for each quicklime dose evaluated, as can be seen in Figure 4.1. The largest dose of quicklime, 15%, showed the quickest response to mixing by raising the temperature above 75°C in 12 minutes. The 15 % quicklime trial also maintained the highest temperature throughout the 40-minute mixing period. Likewise, the lowest dose of quicklime, 5 %, yielded the lowest temperature with a maximum of 49°C.

Comparing the tests of the same quicklime dose with differing moistures, another trend may be seen. During the initial reaction between the manure and quicklime, it appears that higher moisture manure resulted in greater increases in temperature. This is possibly due to a quicker dissolution of the quicklime where more water exists in the higher moisture manure. In this instance exothermicity would be higher initially as the quicklime is hydrated. Although Figure 4.1 indicates that quicklime dose is a more important factor than initial moisture content influencing temperature increase, it should be noted that the differences in moisture content were relatively small, 68 to 72 % moisture.

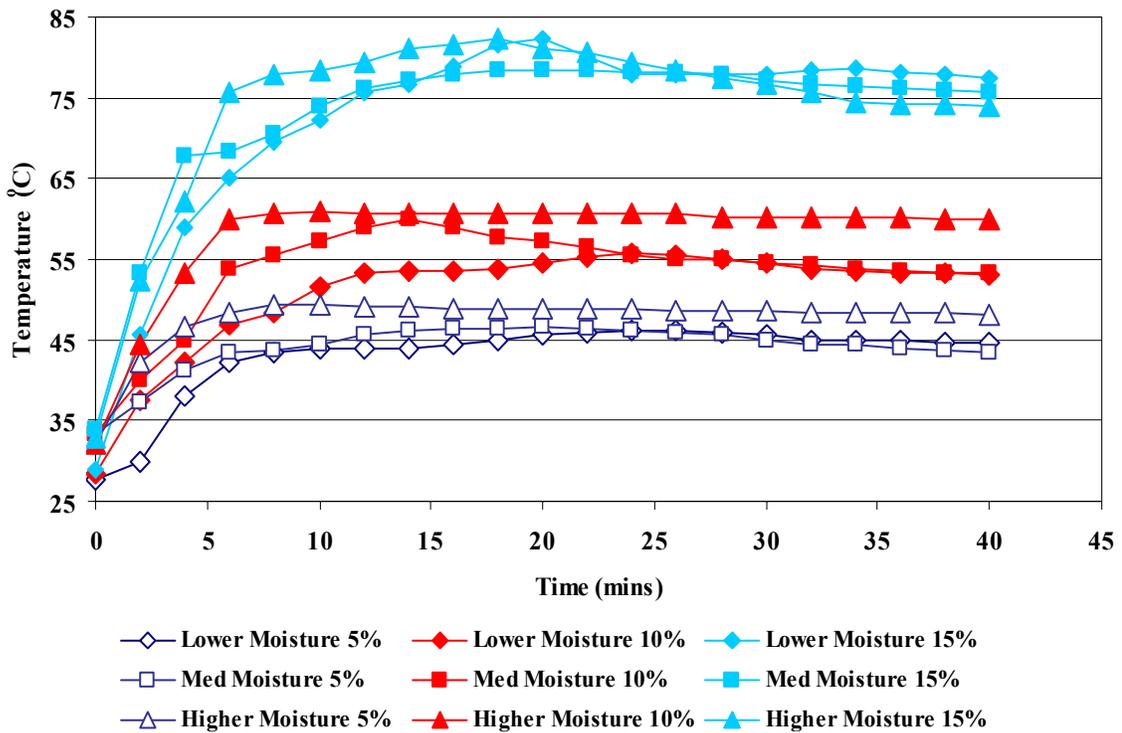


Figure 4.1. Temperature profile for three manure moisture contents and three quicklime doses.

Elevated temperature is critical for killing pathogens. Related data is given in the pathogen propagation section of the storage results (Section 4.2.8). Due to the fact that a reaction temperature of 50°C for 20 minutes during mixing is required for Class-A biosolids, the 5% quicklime doses are insufficient to meet either of these requirements. The 5% quicklime dose was subsequently dropped from the experimental protocol for subsequent phases of this research, as it apparently will not result in a stabilized product meeting the CFR40 requirements.

4.2.2 Mixing pH Profile

The pH of the reaction between the manure and quicklime is also important for the removal of pathogens according to CFR40. The pH change was more drastic for the greatest quicklime dose of 15 % and less so for the 5 % doses. All of the doses tested eventually resulted in a pH of 12.5 or higher during the first 12 minutes of mixing and remained at this level for the entire 40-minute mixing period.

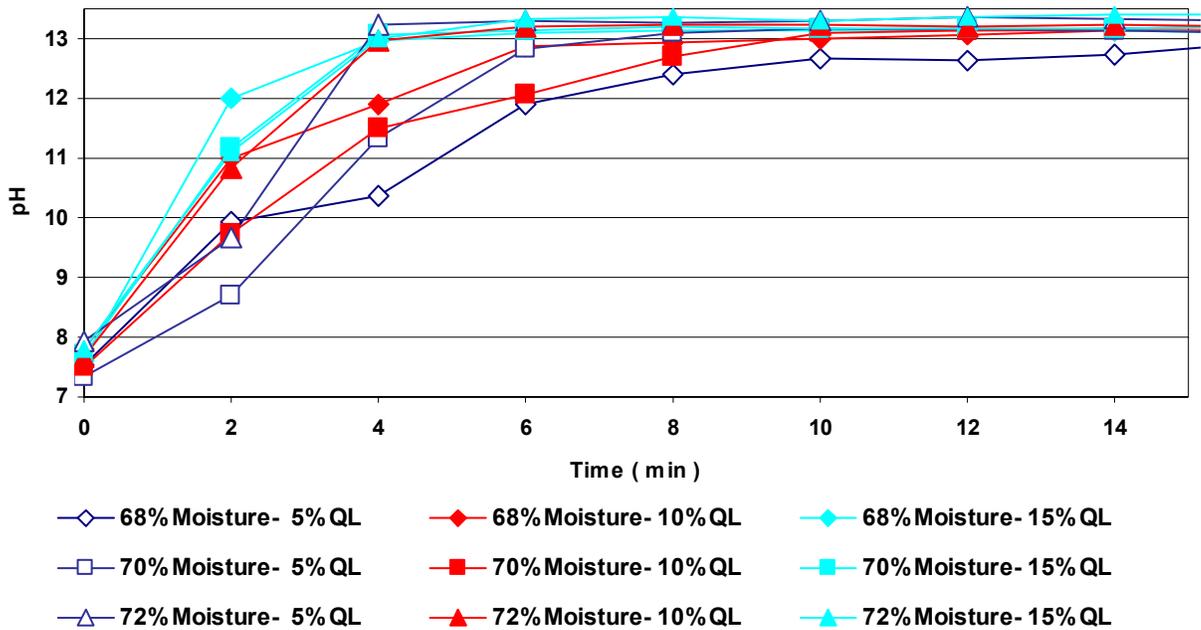


Figure 4.2. Initial pH change with quicklime addition.

It can also be seen that in the highest moisture content manure, all of the doses resulted in a quick pH change, and reached a value near 13 within four minutes of mixing. All of the doses met the pH requirements of the CFR40, for the mixing time period. The CFR40 also requires that the pH must remain above 12 for a two hour period and remain above pH 11.5 for the next 22 hours for pathogen and vector attraction

reduction. Data corresponding to this qualification information is given in section 4.3.8 (Pathogen Kill and Regrowth).

4.2.3 Post-mixing Ammonia Content

The removal of ammonia is of great concern, as larger removals will result in greater allowable application rates of the stabilized product to agricultural soils if nitrogen is used as the basis for application. Each moisture-related batch was collected on a separate day for testing. Figure 4.3 shows a loss of 77 – 85 % for all of lower moisture manures. At the medium and higher moisture manures tested ammonia volatilization was considerably greater with observed reductions in NH₃ between 94 and 97 %.

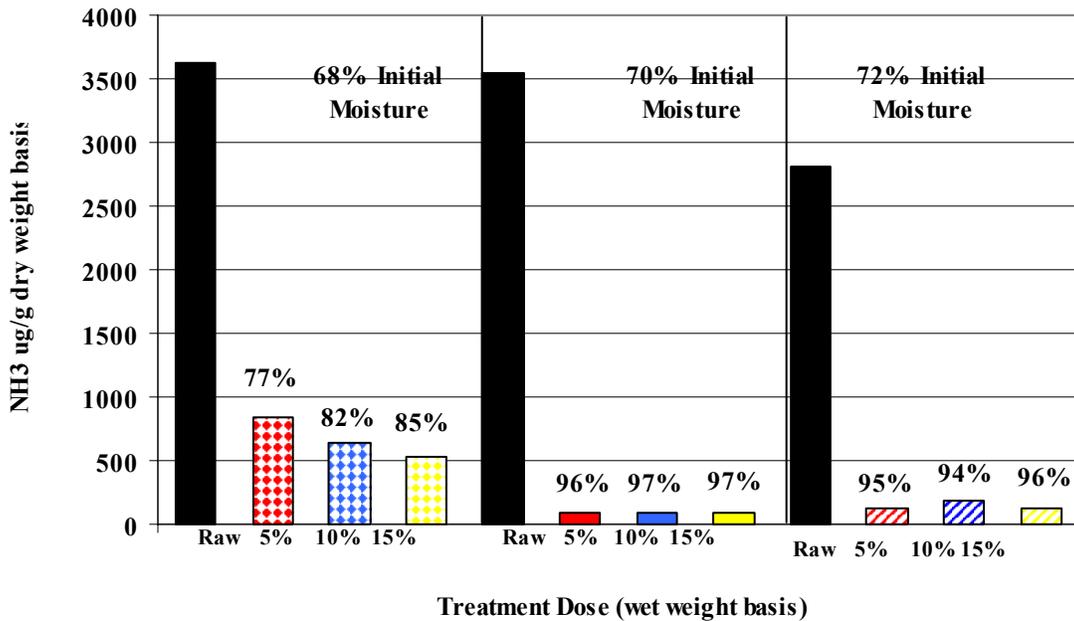


Figure 4.3. Ammonia loss after 40 minutes of mixing. Percent removals are shown above each column.

A trend of increasing ammonia removal with increasing quicklime dose can be seen for the lower moisture trials. This removal trend is not evident among the medium and high moisture trials, and all observed removals were with 3 %. It should be said however that the time between sample collection and sample analysis was greater for the medium and high moisture content tests.

4.2.4 Post Mixing Moisture

Figure 4.4 shows the moisture content for the different doses compared to the original moisture contents.

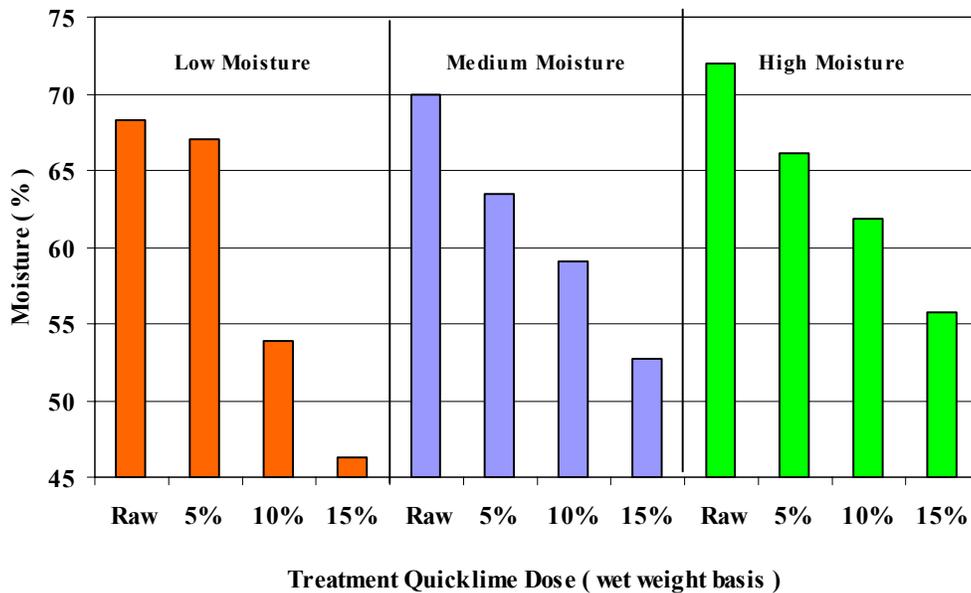


Figure 4.4. Moisture content of raw and processed manure.

The residual moisture shows the pattern of increased drying for greater quicklime doses. One of the CFR40 requirements is the eventual drying of the product to 50 % moisture before use. Only the 15 % quicklime dose under the driest conditions produced

a stable solid meeting this requirement immediately following mixing, reducing moisture to 46.5 %.

4.2.5 Available Phosphorus

Available phosphorus was nearly identical for the raw manures, as was the amount of available phosphorus in the stabilized product. This can be seen in Figure 4.5. A large portion (94.5-99 %) of initially available phosphorus is made temporarily unavailable. This is most probably due to the locking effect of high pH and the availability of calcium from the quicklime for binding producing calcium phosphates. This is considered beneficial as the phosphorus is not lost, but will slowly be made available as the pH decreases and the solubility of the phosphate compounds increase. This will happen gradually as a portion of the reacted lime will re-slate as CO₂ is absorbed from the atmosphere to combine with the quicklime CaO and Ca(OH)₂ to form CaCO₃ the main mineral in limestone.

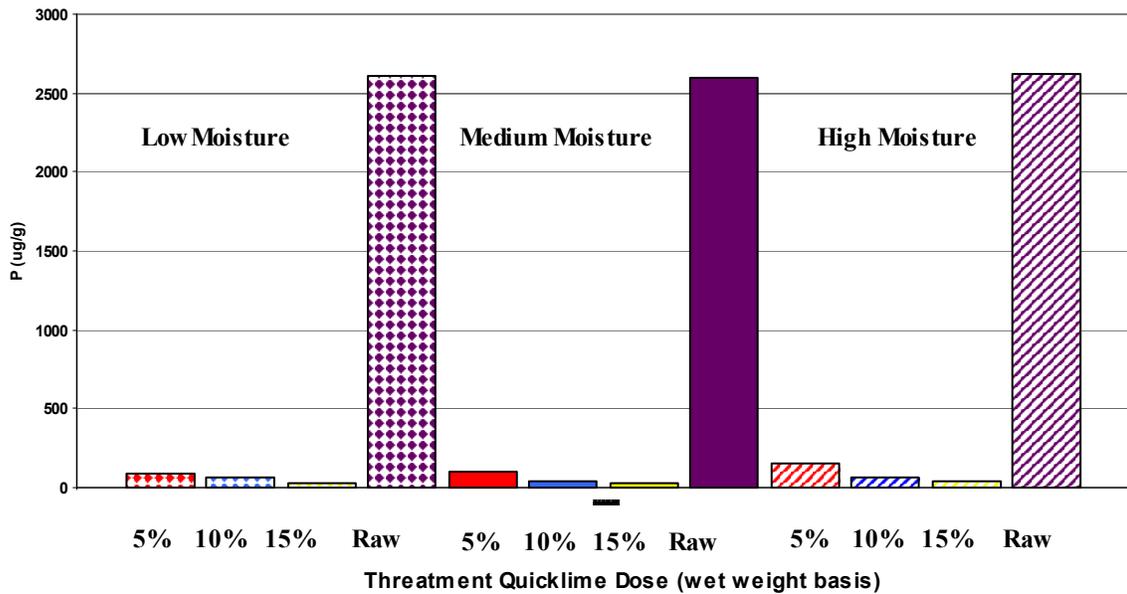


Figure 4.5. Reduction in available (Mehlich III) phosphorus during 40 minutes mixing.

4.2.6 Stabilized Product pH Profile During Storage

As indicated previously the CFR requires that lime-stabilized Class-A biosolids retain a pH of 11.5 for 24 hours after treatment. Figures 4.6 to 4.8 show the pH trend for the different trials over an extended time period.

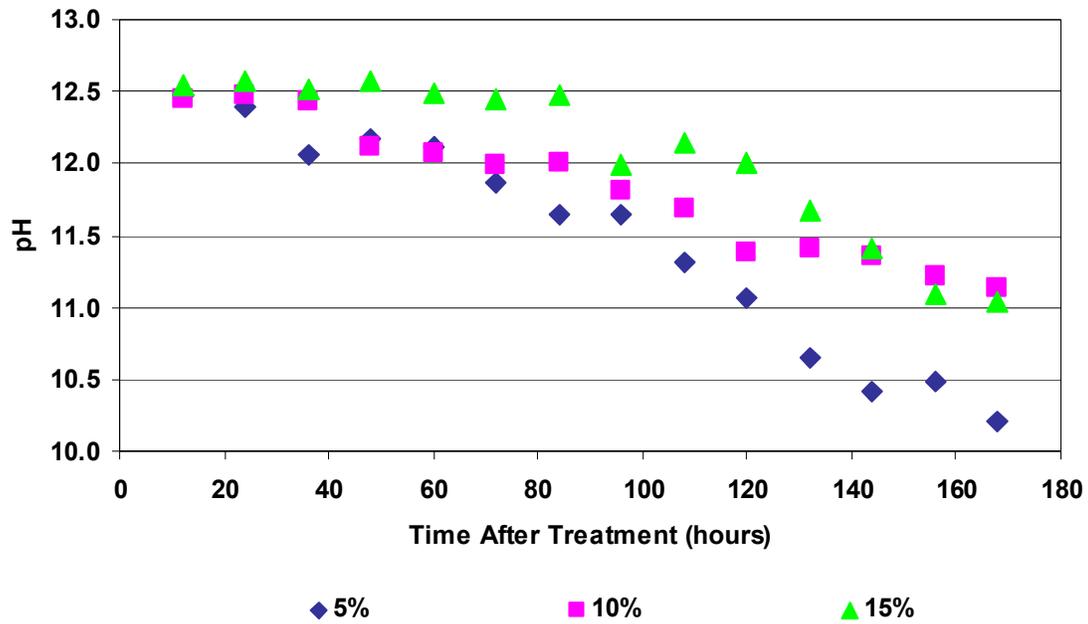


Figure 4.6. pH decline for the low moisture (68%) trials.

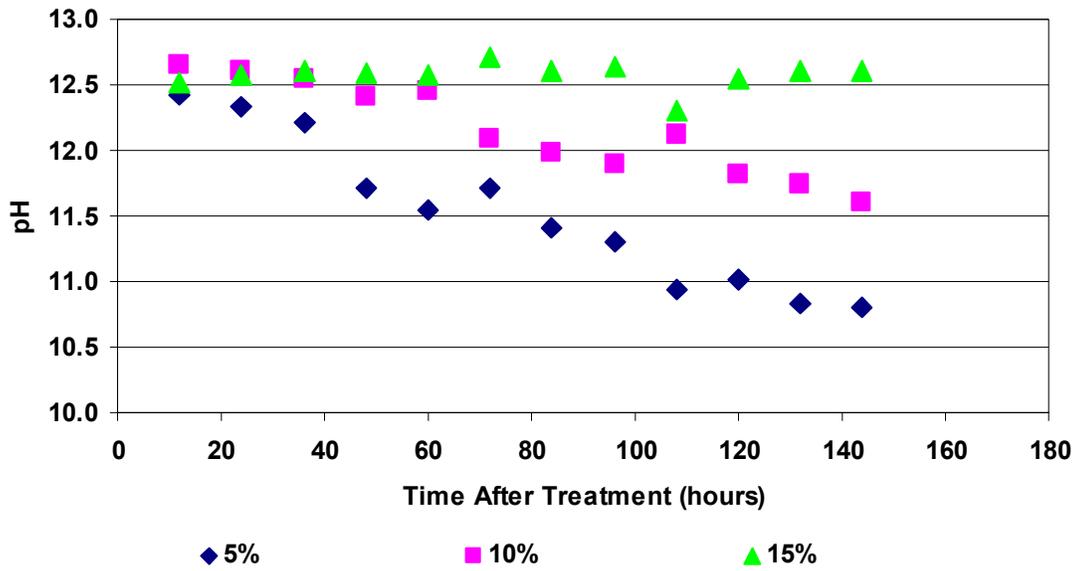


Figure 4.7. pH decline for the medium moisture (70%) trials.

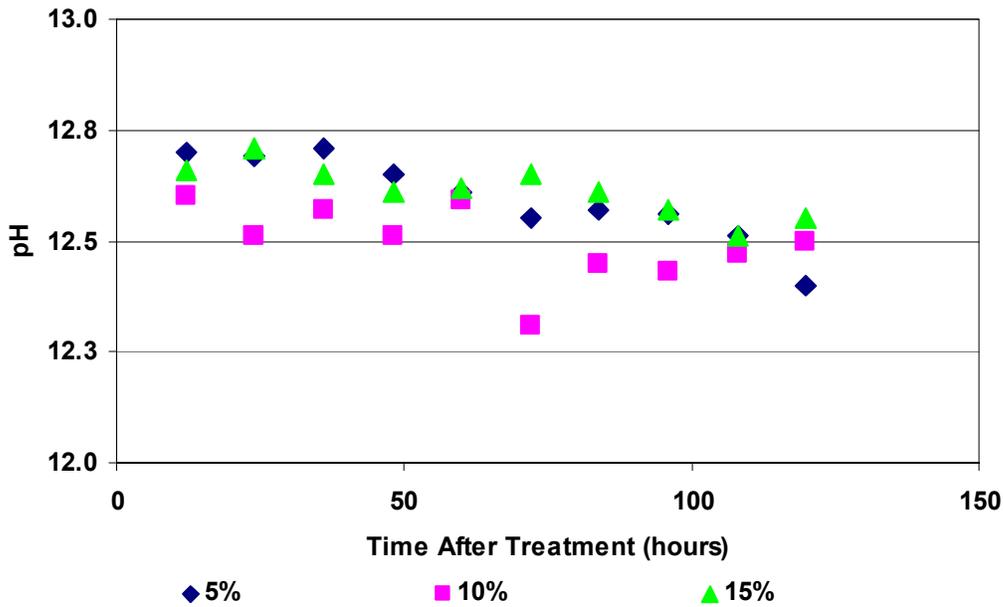


Figure 4.8. pH decline for the high moisture (72%) trials.

The decrease in pH can be attributed to atmospheric equilibration with CO₂. As previously discussed, this will cause CaO or Ca(OH)₂ to combine with CO₂ from the air

and create CaCO₃ (calcium carbonate). The effect is termed re-slating. Gradual decline in pH was recorded until the solids probe did not have enough moisture to operate properly and pH measurements became erratic due to the low moisture residual in the product. Measurements with the solids probe was then discontinued to prevent the recording of unreliable data or damaging of the pH probe.

It can be seen in Figures 4.6 to 4.8 that the pH requirement set forth by the CFR40 regulation (pH 11.5 after 24 hours) are met by all the doses at all moisture contents tested. The highest moisture trials were more uniform in pH decline. This may be due to an increased distribution of dissolved quicklime during testing, allowing for a more homogenous distribution of the alkaline material during the mixing phase.

With respect to the low and medium moisture manures, a higher pH was retained at a higher quicklime dose. At 4 days after treatment, the 15 % doses held at pH 12 or greater. The lower quicklime doses of 5 % showed a significant pH decline after four days compared to the 10 % and 15 % trials for the medium and low moisture contents. The pH decline of the medium moisture manure tests are a good example of the stratified results as they are related to dose and re-slating.

4.2.7 Residual Moisture

The CFR40 moisture restriction for a Class-A biosolid states product must be dried to 50 % moisture or less. The heat generated during mixing helps to achieve this goal as well as the reduction of moisture through the hydration of the quicklime. Figures 4.9 to 4.11 show the stabilized manure moisture during storage for each of the three doses.

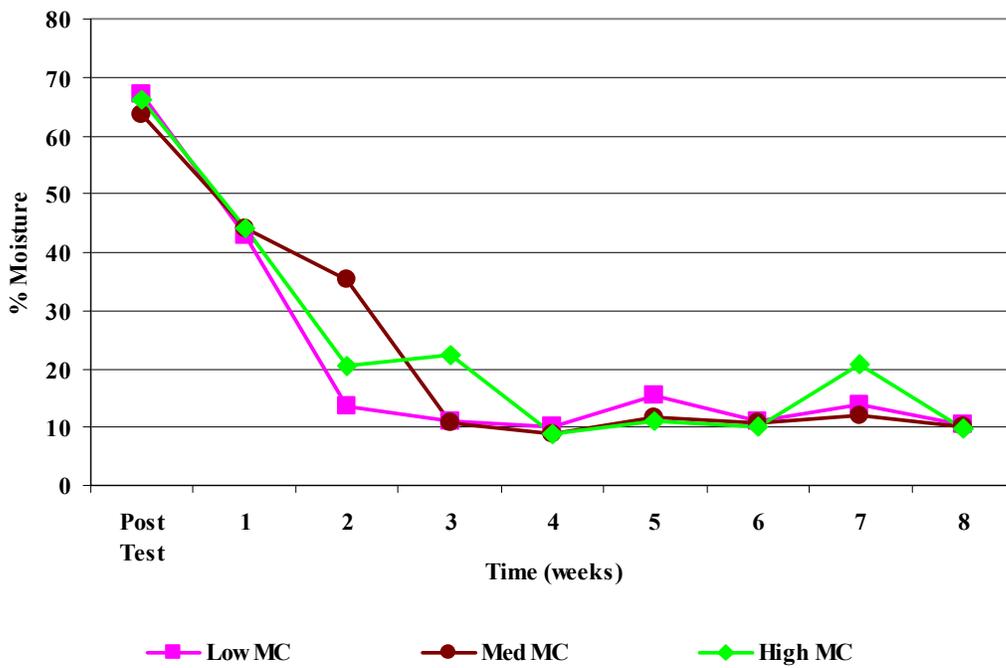


Figure 4.9. Residual moisture after treatment monitored weekly for the 5% quicklime dose.

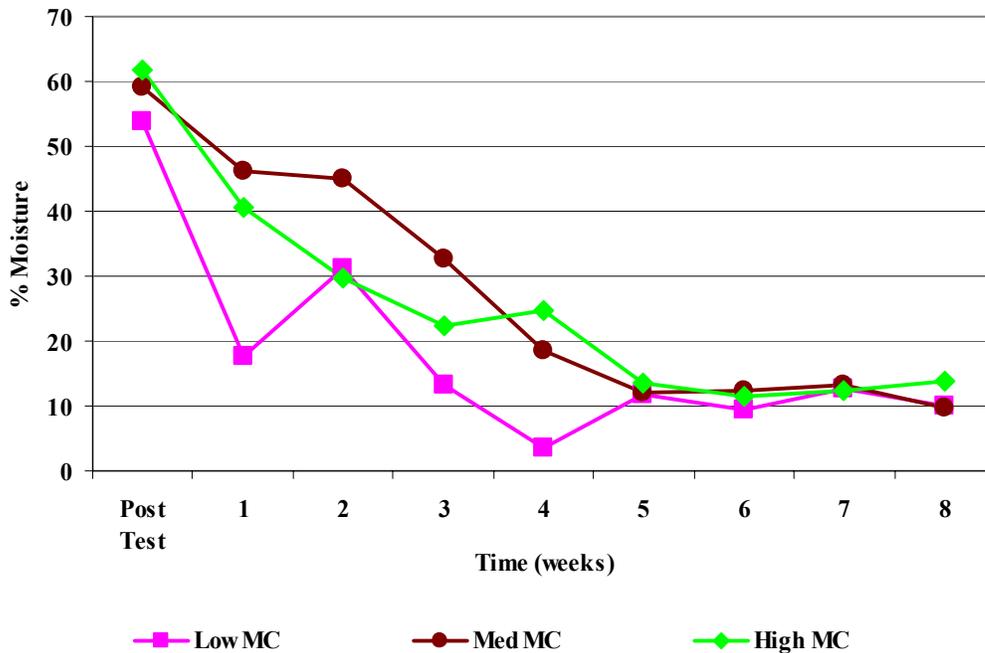


Figure 4.10. Residual moisture after treatment monitored weekly for the 10% quicklime dose.

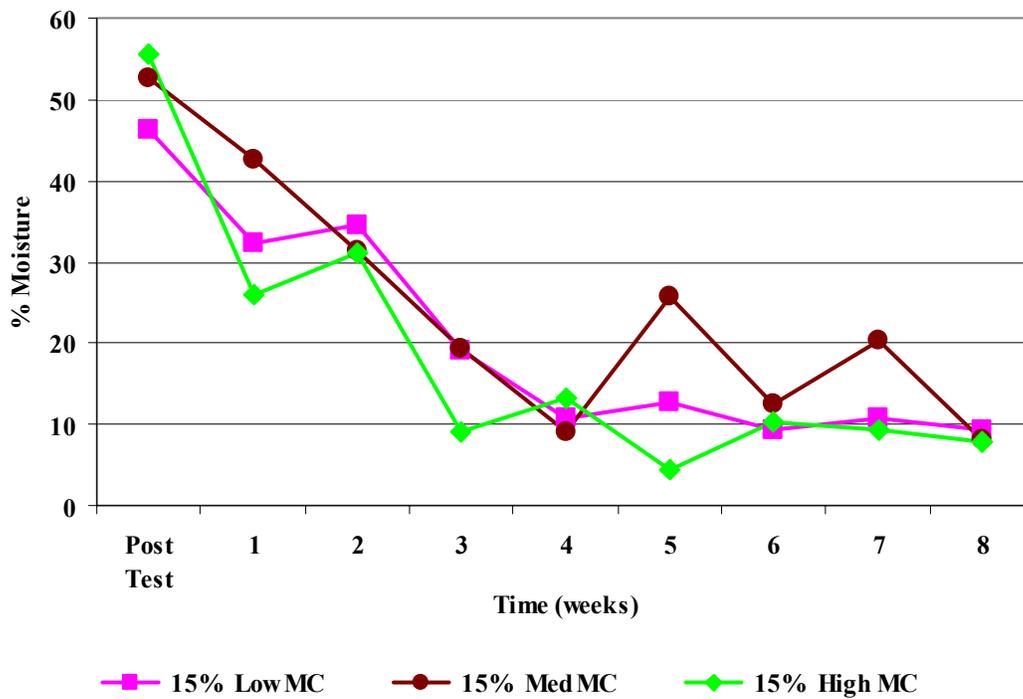


Figure 4.11. Residual moisture after treatment monitored weekly for the 15% quicklime dose.

All of the moisture contents at all doses show a general decline to approximately 10% moisture after four weeks of storage. It is realized that breaking up of the process solids or spreading for more surface area can increase the rate of drying. However, the solids were left as undisturbed as possible after treatment and before sampling.

Fluctuation in moisture content after 4 weeks is likely due to local precipitation and adsorption of water from atmospheric humidity, as wind was allowed to move across the surface of the product. Direct infiltration was prevented by an A-frame tin roof directly above the product, and runoff water was prevented from mixing with the product by redirection using a one meter cinderblock wall.

To understand sudden spikes in moisture near the end of the observation period, it should be noted that there was significant rain on three days in week five and rain on four days during week seven. The storage being outdoors was covered but well ventilated. The atmospheric humidity may have contributed to the moisture rise during these periods.

4.2.8 Pathogens Kill and Regrowth

Although the CFR40 pathogen requirements are met simply by fulfilling the pH and temperature goals, it is desired to know for certain to what extent re-growth will occur during the storage period. The processed solids were analyzed weekly for pathogen growth by serial dilutions to determine the most probable number (MPN) of viable organisms. Although many of the pathogen analyses gave only a less than concentration for the pathogen population, these data are still interesting when looking at the prospect of long term product safety. Figures 4.12 to 4.14 below show the rate of coliform repopulation for the three moisture contents.

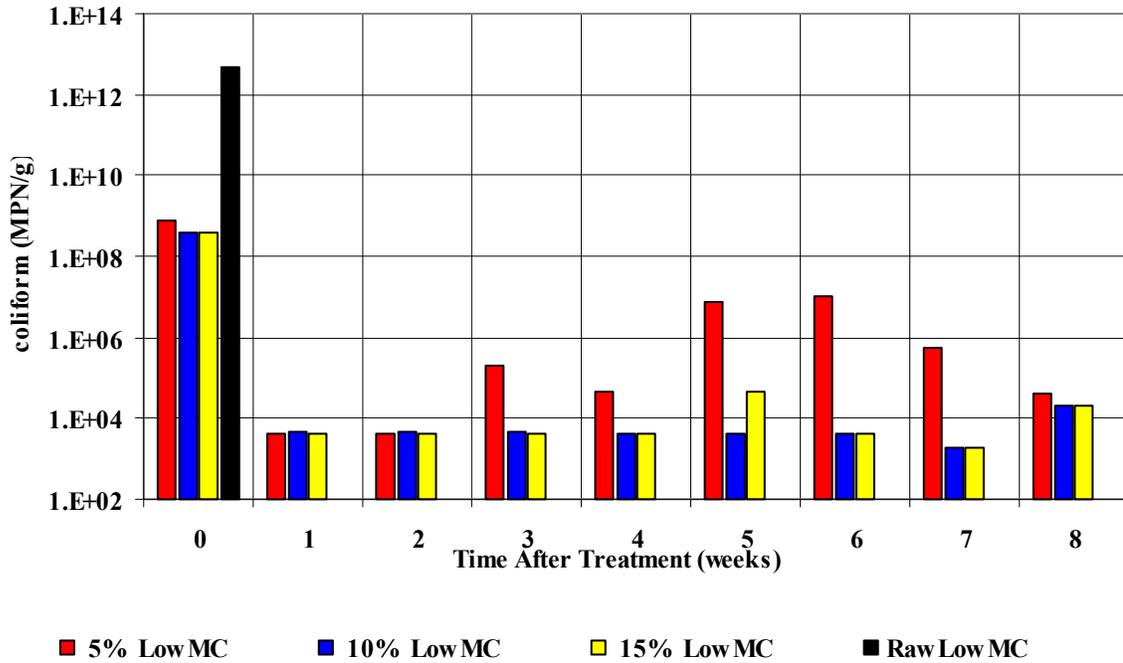


Figure 4.12 Coliform repopulation for the low moisture manure for 5%, 10%, and 15% quicklime addition over a 2 month storage period.

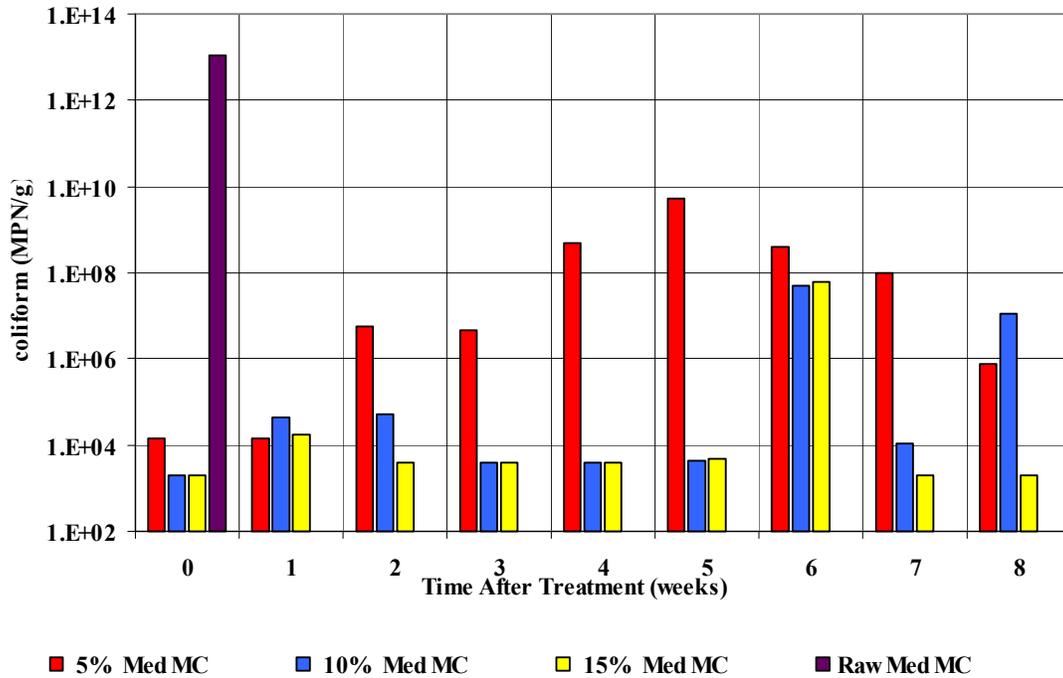


Figure 4.13 Coliform repopulation for the Medium moisture manure for 5%, 10%, and 15% quicklime addition over a 2 month storage period.

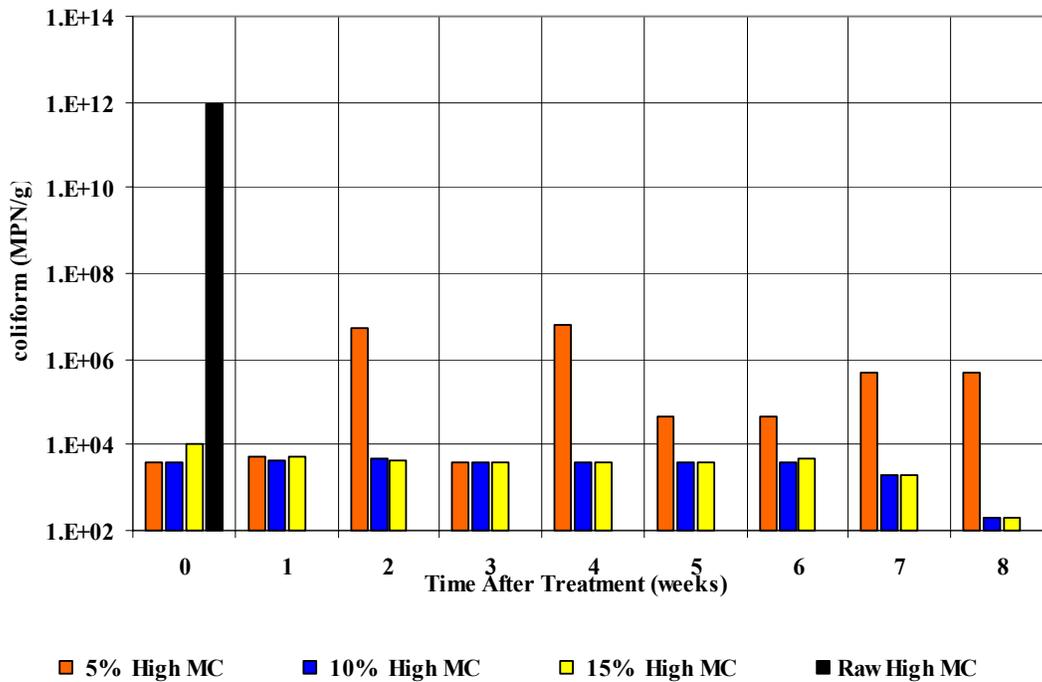


Figure 4.14 Coliform repopulation for the high moisture manure for 5%, 10%, and 15% quicklime addition over a 2 month storage period.

It can be seen that immediately after the test all doses worked well to reduce viable coliform for the medium and high moisture manures. The lower moisture manure had a lower coliform removal immediately after the test for all three doses. This may be due to a slower dissolution of the quicklime and therefore less penetration by the alkaline material initially, however allowing a week for diffusion, the coliform counts changed to a level equivalent with the higher moisture manures with equal doses of quicklime. After seven days all of the doses had relatively good pathogen kills with a reduction by eight orders of magnitude.

All of the graphs show a higher regrowth rate for the 5 % doses as opposed to the higher doses of 10 % and 15 % after four to five weeks. Likewise, the highest dose (15 %) showed the least regrowth at the end of the observation period of eight weeks. It can

be noticed that the medium moisture batch at 10% quicklime had a comparatively large regrowth of coliform on weeks following significant rain (weeks six and eight). Similar graphs were constructed to observe the level of *E. coli* in the treated manure post-test and weekly throughout storage. These are shown in Figures 4.15 to 4.17.

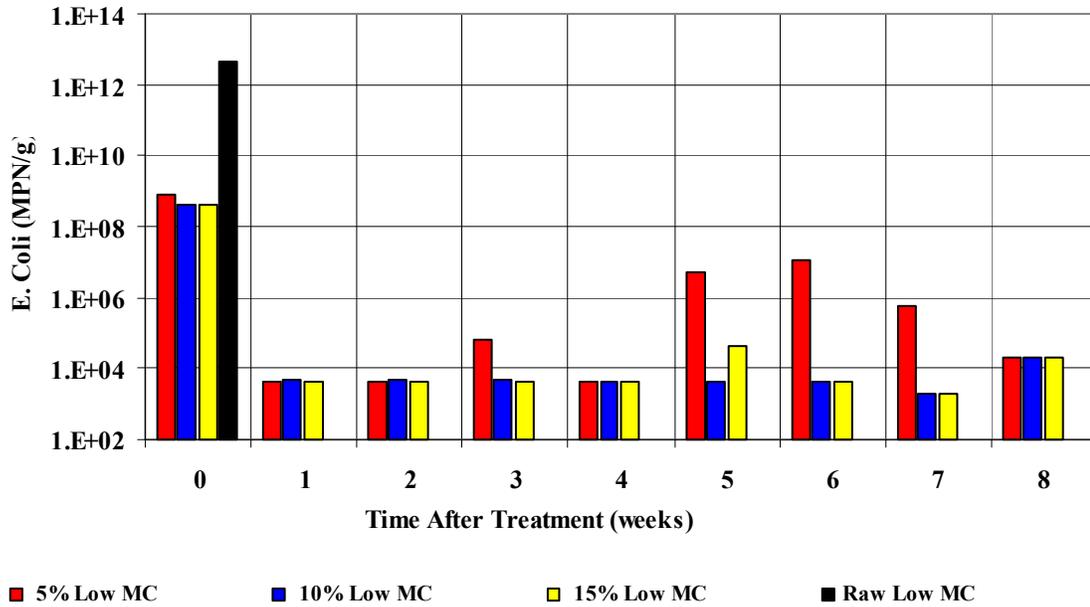


Figure 4.15. *E. coli* repopulation for the low moisture manure for 5%, 10%, and 15% quicklime addition over a 2 month storage period.

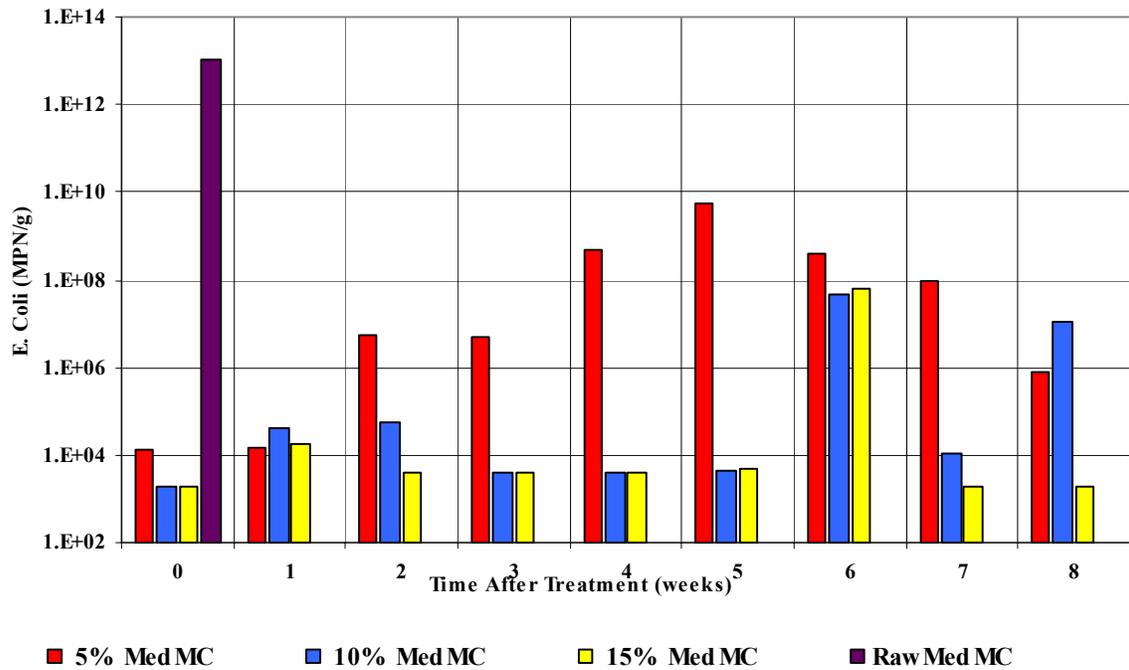


Figure 4.16. *E. coli* repopulation for the medium moisture manure for 5%, 10%, and 15% quicklime addition over a 2 month storage period.

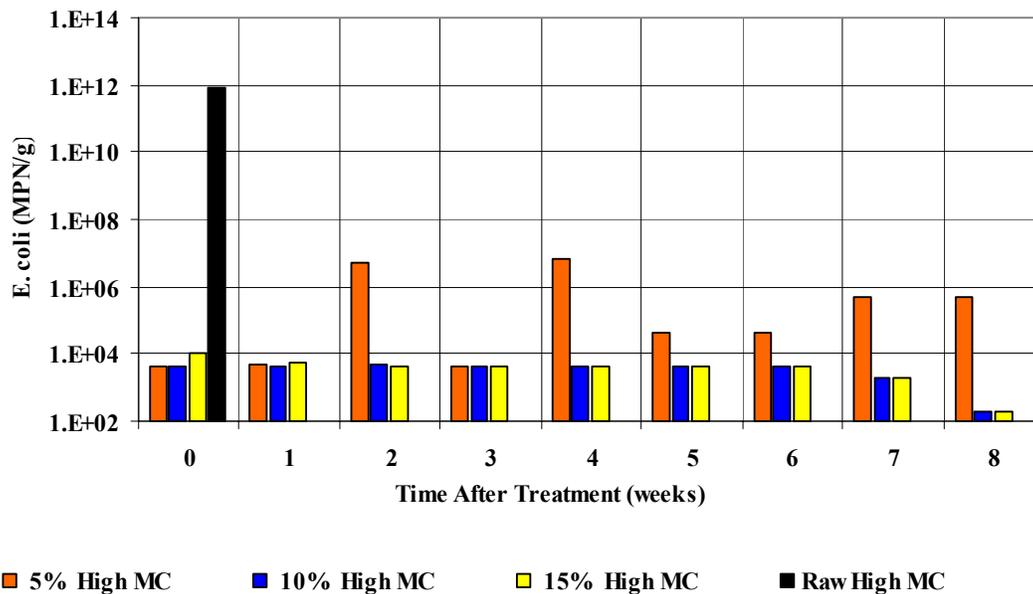


Figure 4.17. *E. coli* repopulation for the high moisture manure for 5%, 10%, and 15% quicklime addition over a two month storage period.

The data for *E. coli* are very similar to the data for coliform during the storage period. Again, treatment of the lower moisture manure was less effective in reducing pathogens initially. But after a one-week storage period, the *E. coli* counts were as good or better than those for the higher moisture batches. Likewise, the 5 % doses had the fastest regrowth for all moisture values. Also, the regrowth on weeks following significant rainfall events (weeks 6 and 8) for the 10 % quicklime dose at the medium moisture content was evident for *E. coli* as well.

The highest moisture batches showed a continual decline of *E. coli* for the 10 % and 15 % doses throughout the testing period. Perhaps this is an indication that if a sufficient amount, 10 % to 15 % quicklime, is added to manure with enough moisture to hydrate the quicklime and penetrate the manure thoroughly, pathogen regrowth is significantly less. The regrowth of pathogens in the manure dosed with 5 % quicklime corresponds to the lower reaction temperatures and declining pH for the tests conducted at the minimal dose.

4.2.9 Quicklime Stabilized [NH₃]

After storing stabilized manure samples for 1 week, ammoniacal nitrogen was decreased by >90 % for all manures and quicklime treatments evaluated (Figures 4.18 to 4.20). Ammonia volatilization during the test (1 hour after mixing) was greater for the medium and high moisture manures. All of the manures had an increase in ammonia after 6 weeks of storage. At this period pathogen regrowth was also observed. It is likely that as regrowth occurred ammonia was produced as a product of the mineralization of organic material containing nitrogen. Figures 4.18, 4.19, and 4.20 give residual ammonia

concentrations (per gram solids) for quicklime treatments to manure with low, medium, and high moisture contents.

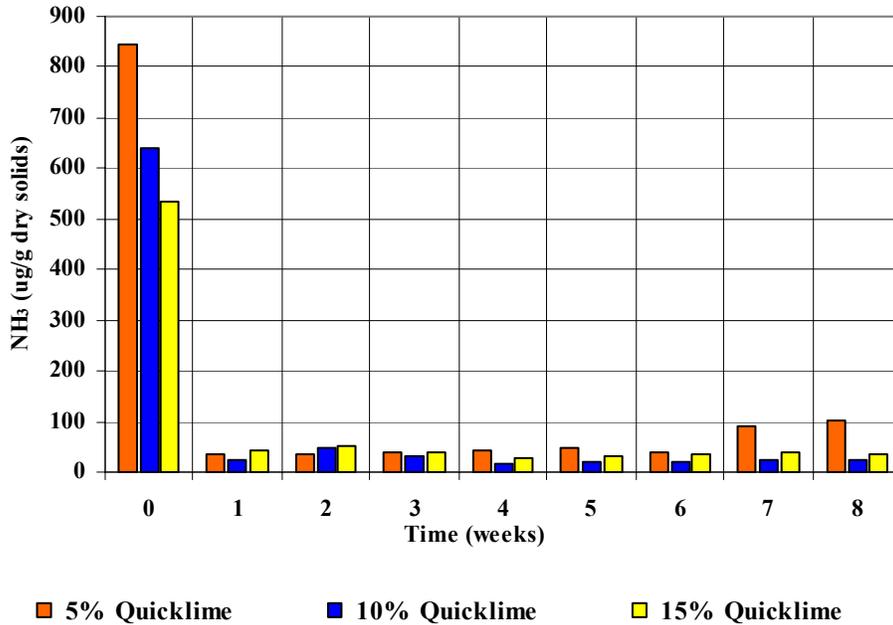


Figure 4.18. Ammonia residuals for low moisture manure stabilized with 5%, 10%, and 15% quicklime. Raw ammoniacal nitrogen = 3625 ug / g dry solids.

The low moisture manure showed a correlation between dosage and residual ammonia contained within the stabilized product one hour after the test. After one week the ammonia remaining in the product was minimal (<50 $\mu\text{g/g}$ solids) for all doses. The product then remained stable with slightly decreasing ammonia concentrations until week seven, when NH_3 in the 5% quicklime treated manure increased by about two-fold. This increase followed an increase in pathogen count at five to six weeks for the 5% low moisture batch (see Figures 4.12 and 4.15). The 10% and 15% doses showed the same consistent low ammonia concentrations for the lower moisture manure throughout the observation period of eight weeks.

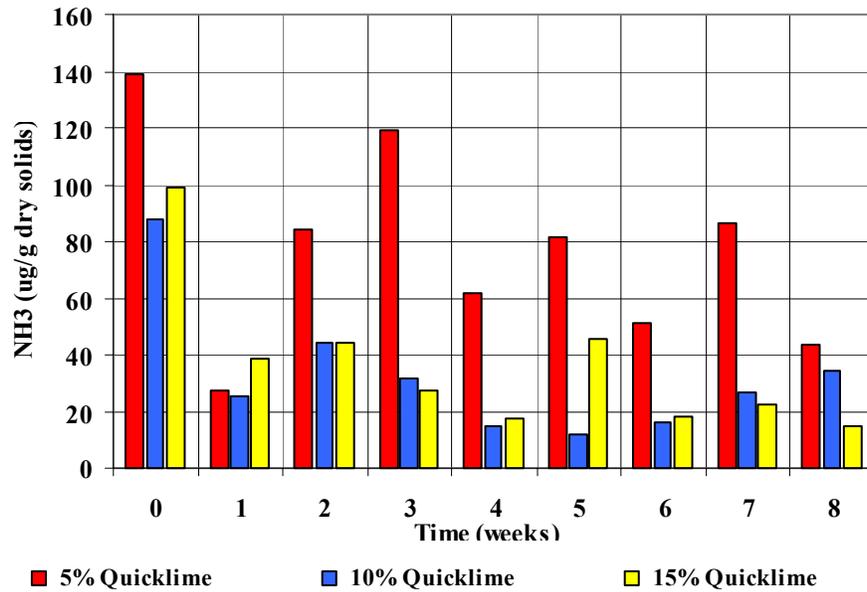


Figure 4.19. Ammonia residuals for medium moisture manure stabilized with 5%, 10%, and 15% quicklime. Raw ammoniacal nitrogen = 3540 ug / g dry solids.

With regard to the medium moisture manure, lower residual ammonia concentrations were observed directly after the test as compared to the low moisture stabilized manure. However, just as with pathogen kills after one week of storage, the remaining ammonia was very similar for the 10 and 15 % quicklime experiments. The 5 % quicklime experiments ad significantly larger residual NH₃ in the stored product. Similar to the low moisture trials, the medium moisture manure had a larger amount of ammonia remaining during the remainder of the observation period than the 15 % quicklime dosed manure solids.

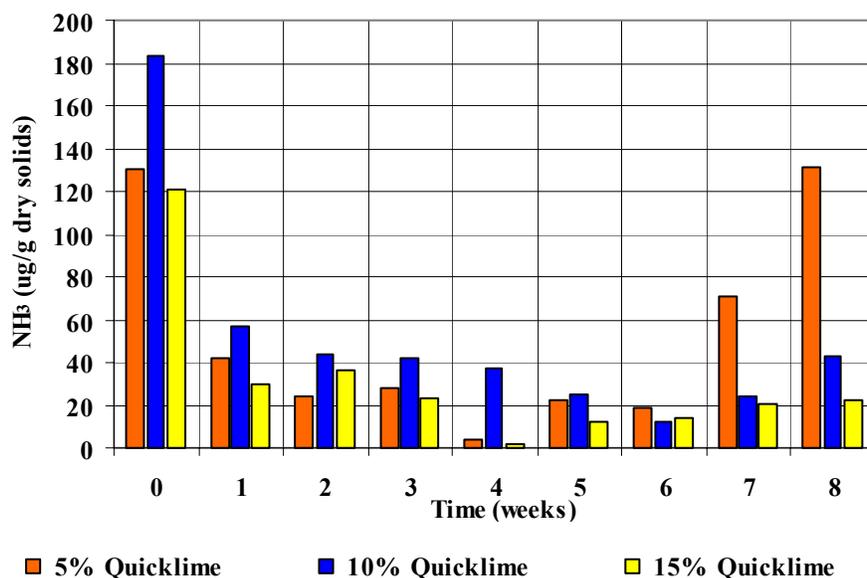


Figure 4.20 Ammonia residuals for high moisture manure stabilized with 5%, 10%, and 15% quicklime. Raw ammoniacal nitrogen = 2813 ug / g dry solids.

The highest moisture manure tested show results similar to the medium moisture manure in that there was a decrease for six weeks after treatment, followed by a significant increase in the ammonia residual of the 5% quicklime treated batch beginning at week seven. This increase corresponded to an increase in moisture in the 5% - high moisture test, which can be seen in Figure 4.9. As with the other moisture contents, NH₃ in the 10 % and 15 % quicklime trials residual stayed at a low level (50 µg/g solids) for the duration of the storage period.

In comparison of the three moisture contents treated, both the medium and high moisture content manure showed a greater immediate removal of ammonia from the solids product. This difference becomes insignificant after a storage period of one week. Looking at all moisture contents the 10% and 15% quicklime doses showed a continuous

advantage over the 5% dose with respect to ammonia remaining in the stabilized product. This may be due to the remaining alkaline material in the higher dosed products, which serve to keep the pH at a higher level for a longer period of time.

4.2.10 Available P

The plant availability of phosphorus present in a soil is primarily a function of pH. Phosphorus availability is greatest in the pH range of 5.5 - 7 and decreases at higher pH levels. Because the phosphorus is not lost through any understood mechanism of stabilization, one should understand that it has precipitated into a form which is not dissolved through the weak acid extraction (Mehlich III) performed for the detection of plant available phosphorus. Figures 4.21-4.23 show the amounts of soluble phosphorus in the raw manure and stabilized product that can become usable to plants (dissolved) under conditions similar to those at the rhizosphere, with respect to pH and depending on the pH and acidity of the soil to which the stabilized solids are applied. It should be noted however that the stored product was not allowed to be infiltrated with precipitation nor was it mixed with soil during the observation period. Both such pH buffering activities would have a decidedly quicker response on reducing pH and allowing phosphorus to be gradually released from the product.

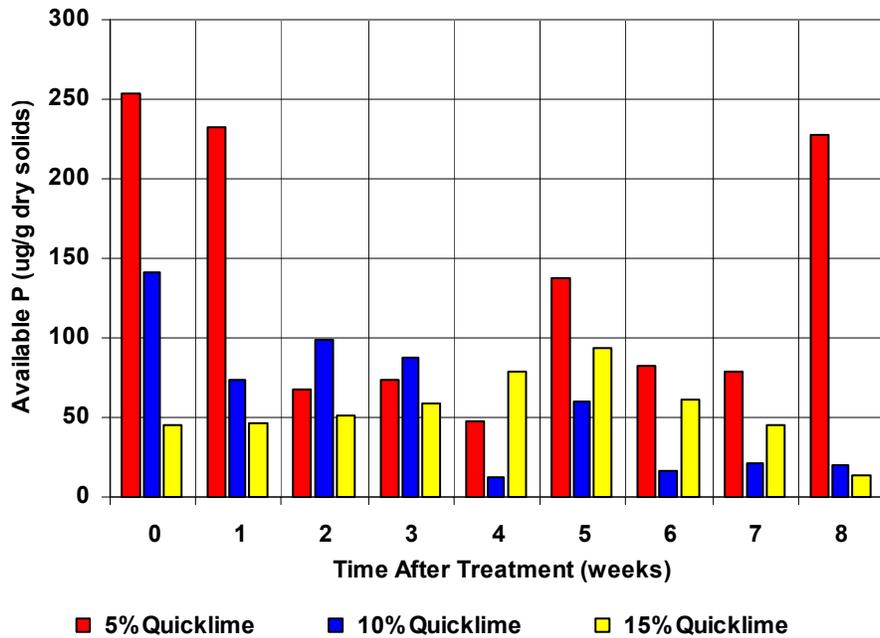


Figure 4.21. 5%, 10%, and 15% quicklime stabilized low moisture manure observed and sampled weekly for 2 months. Raw available phosphorus = 8209 ug / g dry solids.

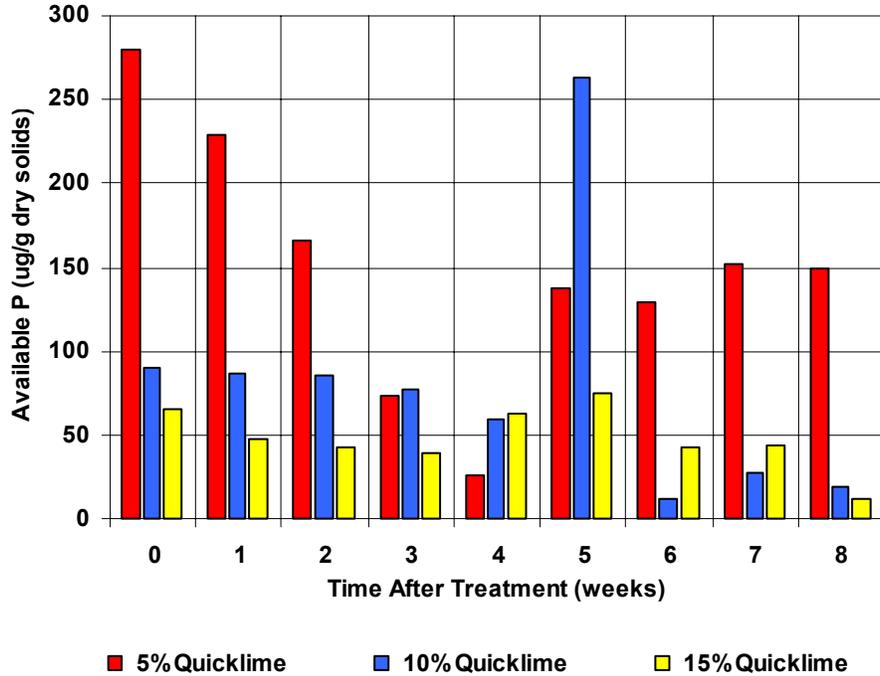


Figure 4.22. 5%, 10%, and 15% quicklime stabilized medium moisture manure observed and sampled weekly for 2 months. Raw available phosphorus = 8659 ug / g dry solids.

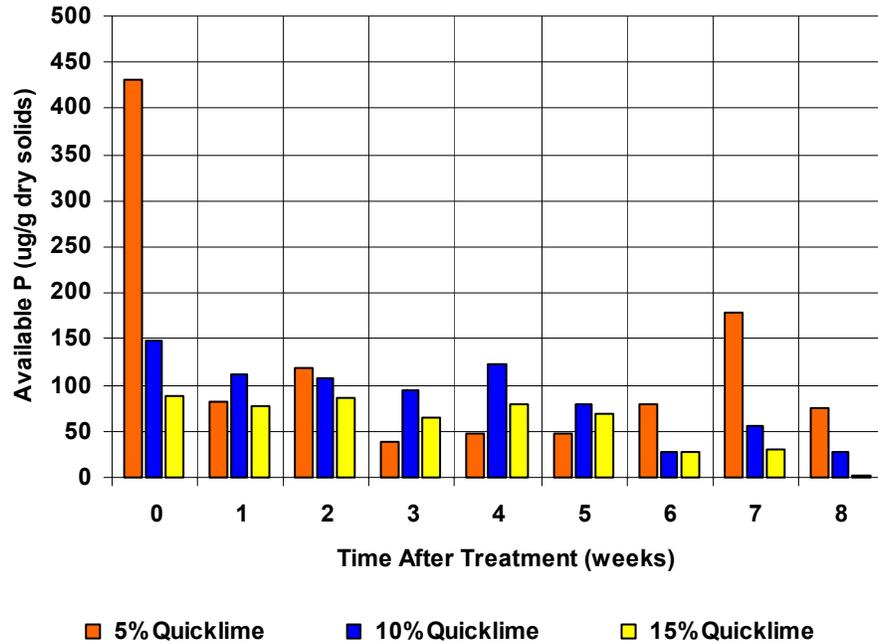


Figure 4.23. 5%, 10%, and 15% quicklime stabilized high moisture manure observed and sampled weekly for 2 months. Raw available phosphorus = 9326 ug / g dry solids.

Regardless of the of moisture contents evaluated, all stabilized manure samples showed similar post-test values for available phosphorus. The trend among the dosage range showed that as the amount of quicklime is increased the amount of phosphorus retained in a non-available form increased immediately after treatment and remained so for as much as a week, particularly in the low and medium moisture manures. On average, the lower dose of 5 % quicklime left more phosphorus available during the eight weeks after stabilization.

For all of the moisture treatments, a dose of 15 % quicklime reduced the available phosphorus to a level near the detection limit for the analysis using the Mehlich III weak acid extraction. Precipitation of calcium phosphates is expected, especially with the

relatively high metal concentrations known to exist in swine manure (Westerman and Bicudo, 2000, Koger et al., 2001). The solubility of these phosphates are well known.

Typical Metal concentrations for separated manure are shown in Table 4.2.

Table 4.2. Average metal concentration of separated swine manure.

Metal	Concentration (ug/g) (Screened)	Error	Concentration (ug/g) (Belt separation)
Ca	37,224	+/- 13,890	21,968
Mg	4,849	+/- 690	NA
K	4,577	+/- 644	20,651
Fe	3,208	+/- 831	1,845
Na	2,210	+/- 437	3,776
Zn	314	+/- 53	850
Cu	131	+/- 40	224

Any iron, aluminum, and eventually calcium precipitate the decreasingly available phosphates as pH increases to a value of nine and beyond. Table 4.2 shows there seems to be an abundance of calcium, which can serve to bind with the phosphates in the manure however, we are adding another 238 mg of Ca per gram of manure solids at a quicklime dose of 10%. A material with the ability to hold phosphates to this degree would serve well as an amendment to increase the phosphate buffering capacity of soils presently unable to retain phosphates added as fertilizer. It appears that the larger doses of 10 % and 15 % quicklime have the capacity to reduce the phosphorus availability to a point where, without a buffer such as soil or water, a dilute weak acid environment such as roots surfaces cannot dissolve the phosphates present in any form. This would serve to prevent unwanted leaching for the stabilized product.

4.2.11 % Nitrogen

Analysis also included the percentage of total nitrogen in the raw and stabilized manure. By knowing the total nitrogen concentration we may determine to what degree stabilization will reduce the total nitrogen content of the product. Storage data has shown the removal of ammonia to be 98-99%, however at the start of the experiment, ammonia made up only about 10% of the total nitrogen in the scraped manure used for this study.

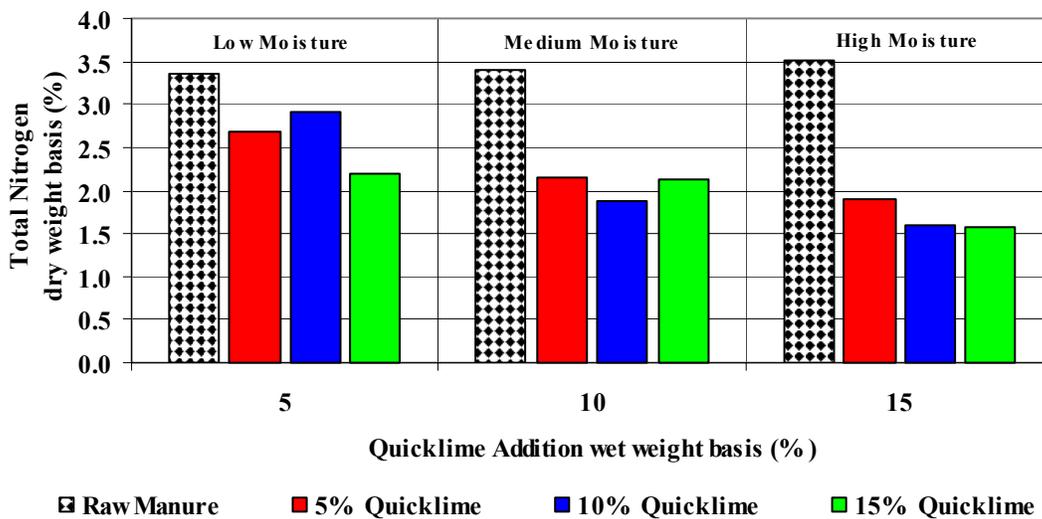


Figure 4.24. Total nitrogen for the raw manure and stored stabilized product eight weeks after quicklime addition.

As shown in Figure 4.24, there is certainly a reduction in total nitrogen. This reduction is however more than the 10 % originally composed by ammoniacal nitrogen. Therefore nitrogen is apparently lost through a source other than ammonia volatilization. Denitrification is unlikely due to the pH and lack of soil organisms. Perhaps as ammonia is volatilized more is made available for evaporation through mineralization by small amount of viable organisms remaining in the product after stabilization. Small numbers of organisms were observed to survive the stabilization process (see Figures 4.12-4.18).

It is also true that more pathogens survived and grew in the 5 % quicklime dosed products. Total nitrogen analysis was performed four to six weeks after stabilization and degradation of organic nitrogen to ammoniacal nitrogen is possible by this length of time.

It would be convenient to explain that increased microbial activity associated with the lower quicklime dose accounted for the increased loss in total nitrogen, but this was not the case. In point of fact, manure stabilized with the lower dose of 5 % quicklime lost less total nitrogen than the higher doses of 10 %, and 10 % quicklime batches lost less total nitrogen than those treated with 15 %. This indicates that as more quicklime is added more total nitrogen is lost for the two months of storage.

It was decided that the failure of 5 % quicklime doses to meet Class-A requirements resulted in the exclusion of doses this low for further testing. It was clear from the long term pH trend for the stored medium and high moisture manures (Figures 4.7 and 4.8) that the 5 % doses had a more rapidly decreasing pH and were therefore less stable in this regard. Manure stabilized with 5 % quicklime also had a larger amount of residual ammonia for all moisture values during the later month of storage (Figures 4.18-4.20), another negative trend. The final factor for removal of the 5% trials was the obvious difference in moisture removal (Figure 4.4) and temperature hike (Figure 4.1) during the mixing period. This pointed toward its failure to achieve the level of drying and temperature required to achieve a Class-A rating under the guidelines of the CFR40.

4.3 Part 3 - One Hour Bench Scale Tests

Ammonia volatilization from the product during mixing was quantified during the testing conducted under Part 4.3. A small one-liter reactor was constructed and fitted

with an acid trap and vacuum system to monitor this phenomenon. Mixing was conducted continuously and acid traps were changed at ten minute intervals to observe the dynamics of the ammonia volatilization rate. Baseline data are presented first for amounts of ammonia collected in air samples and raw manure without quicklime addition. Next, results of the 10 % and 15 % duplicates are shown, followed by the results for a dosage trial using 10 % and 15 % quicklime doses on the same manure.

4.3.1 Background Air Analysis

Ambient laboratory air was tested by operation of the empty manure reactor for 10 minutes with an acid trap and flow rate of three liters per minute. Duplicates for this experiment gave the same result of 17.5 μg of ammonia trapped from the 30 liters of air. The same results are not as extremely precise as it may seem at first because both acid traps contained little more than the detection limit for the ammonia analysis. Round-off errors at this threshold limit may provide a clue as to why both results were numerically the same. This result equates to 290 $\mu\text{g}/\text{m}^3$ for the ambient air in the laboratory.

This amount is above average values for urban areas of 5-25 $\mu\text{g}/\text{m}^3$. However it is far below an amount considered hazardous (18,000 $\mu\text{g}/\text{m}^3 = 25$ ppm) by OSHA. Scientists in Europe suggest that this limit should be reduced to 10 ppm or 7,200 $\mu\text{g}/\text{m}^3$. This level is still 24 times the amount encountered in the lab. The value for the air was considered to be 0.3 $\mu\text{g}/\text{L}$ and used as a background for the rest of Part 4.3.

4.3.2 Ammonia Volatilization from Raw Manure

The ammonia trapped from mixing manure in the reactor in the absence of quick lime was similar to that from the ambient air in the laboratory. The experiment was then repeated to determine reproducibility. Values for the manure alone were again near the threshold value when traps were replaced at ten minute intervals. Although one trap could capture all of the ammonia for the 60-minute testing period, it was desired to see if ammonia loss varied with time during the continuous mixing of the reactor. Therefore, six to ten minute mixing intervals were used for sampling from the acid traps. Figure 4.25 shows the cumulative ammonia trapped during the mixing process for duplicates with the raw manure with moisture content of 65% and an ammonia concentration of 6 mg/g solids.

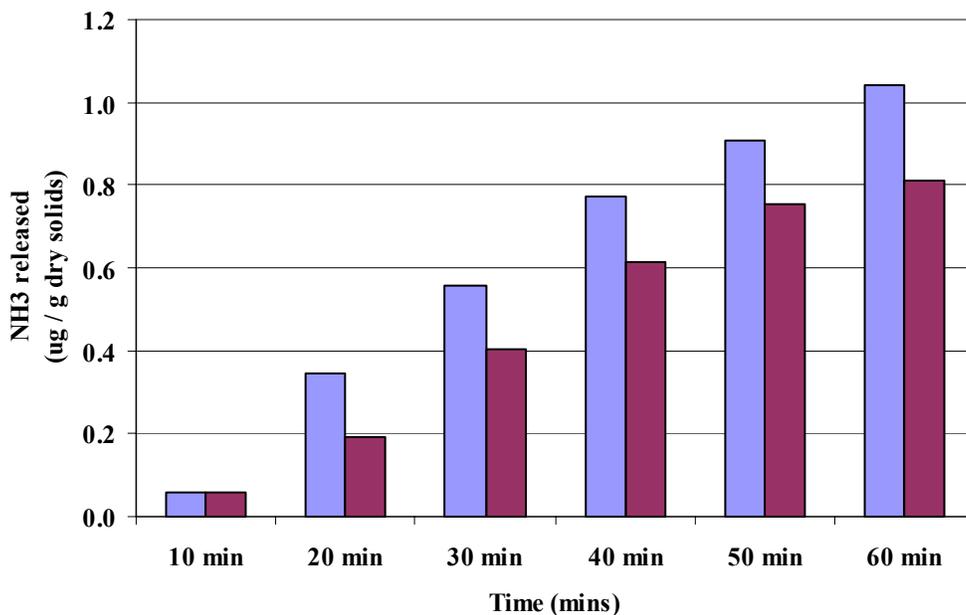


Figure 4.25. Duplicate experiments to measure cumulative ammonia loss from mixing of raw manure.

Initial volatilization for each replicate was identical. Between 10 and 20 minutes into mixing one of the duplicates released about twice as much ammonia gas as the other. For the remaining 40 minutes of mixing ammonia vaporization was the same for the set of tests without quicklime. As shown by subsequent experiments, these releases were insignificant when compared to the amount of ammonia liberated by the addition of quicklime.

4.3.3 Ammonia Volatilization for duplicate experiments at 10% quicklime

The addition of 10 % quicklime to duplicate tests showed a release of ammonia nearly three orders of magnitude greater than that without quicklime (Figures 4.26 and 4.25). Please note the change in units for the dependent variable from ug in Figure 4.25 to mg in Figure 4.26 below.

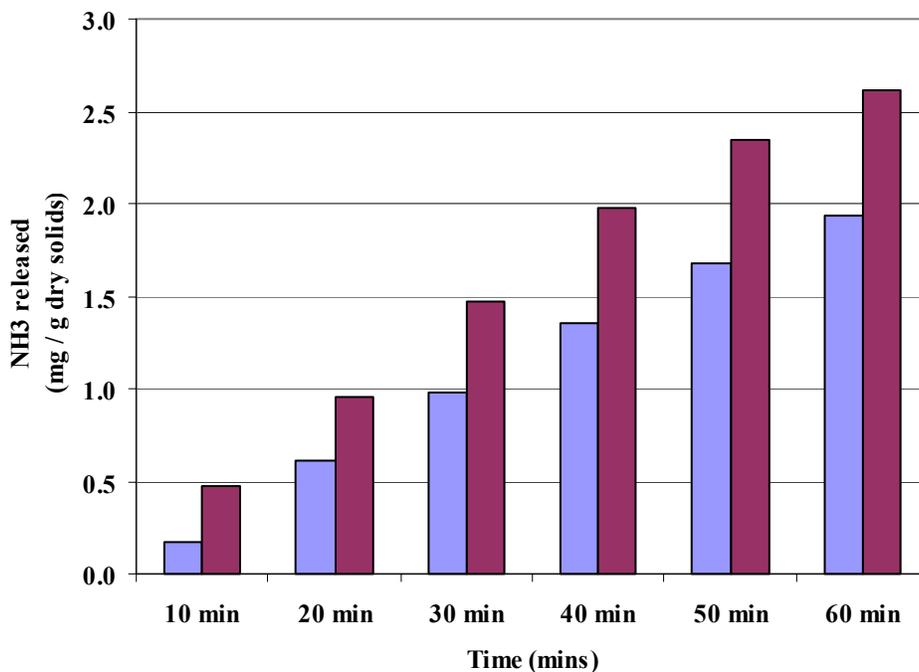


Figure 4.26. Cumulative ammonia volatilization for duplicates using a quicklime dose of 10%. Moisture content = 63%, Initial [NH₃] = 6.7 mg/g solids.

It should be noted that a slight twist of the impeller was made before the addition of quicklime in the second duplicate experiment, shown as the bars on the right of each sample period indicated in the graph. It was unsure if the impeller alteration caused the differences in the ammonia volatilization rate for the duplicates conducted at the 10 % quicklime dose. No alteration was made to the impeller for the 15 % quicklime dosed duplicates to determine if the mixing blade angle was the cause for the differences in the 10% duplicates, or if the differences were due to natural variability of the manure and the mixing process.

During the first ten minutes of mixing, the second duplicate released much more ammonia as a gas, however release for the second ten-minute period was nearly identical. Between the 20 and 30 minute mark the second duplicate again liberated approximately 1/3 more ammonia than the first duplicate, but these differences became less until the difference in was only 7 % for the 50-60 minute time period. It is believed that as the process time lengthens variability in residual ammonia is reduced for similar doses of quicklime. Part 4.4 was designed to test this theory over a one-month period.

4.3.4 Duplicates at 15% quicklime

The ammonia volatilization for duplicates with doses of 15 % quicklime was more similar than the 10 % quicklime duplicates. This was encouraging due the large differences seen with the 10 % quicklime. The similarity also pointed toward the explanation for the differences in the 10 % dose being in the change of the mixing blade's pitch to achieve through mixing.

Differences in the ammonia driven off as a gas seemed to lessen as mixing time progressed (Figure 4.27). This was also seen in the duplicates of 10 % quicklime addition (see Figure 4.26).

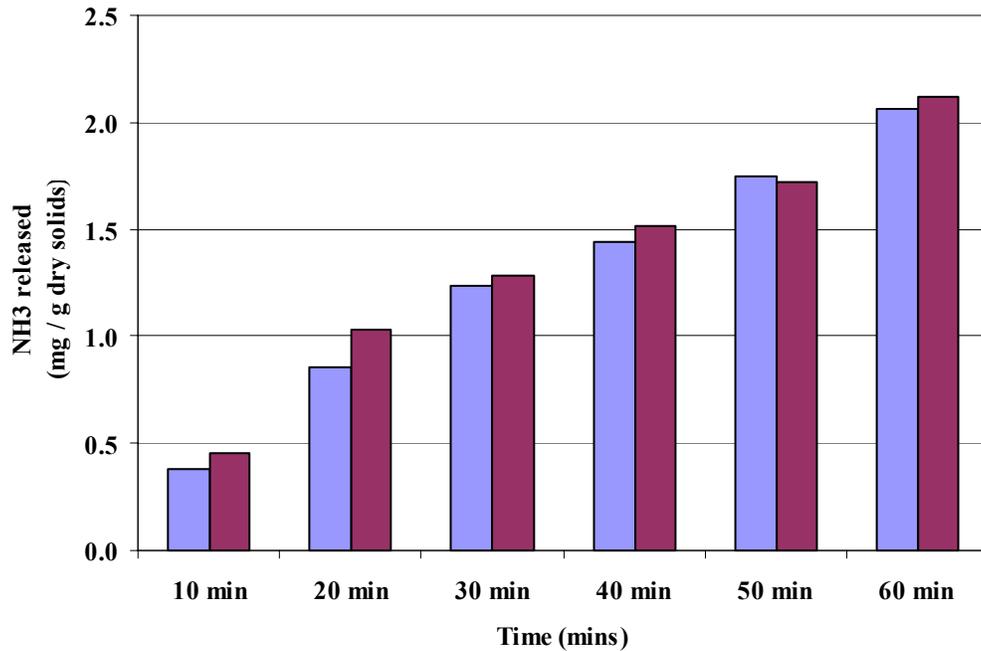


Figure 4.27. Cumulative ammonia volatilization for duplicates using a quicklime dose of 15%. (Moisture content = 64%, Raw [NH₃] = 6.85 mg/g solids).

Most surprising was the fact that after modification by slightly twisting the blades of the blade the 10 % and both of the 15 % doses showed similar removals. The data indicated that for the trials run thus far in Part 4.3, dosage between 10 % and 15 % did not seem to be a factor. For this reason, the next batch of manure was tested for both doses. This was for the purpose of finding differences in ammonia removals for the two doses within the initial 60 minutes of mixing.

4.3.5 10% and 15% quicklime trials

Raw manure was collected daily. Therefore the amount of tests which could be conducted with the same manure was limited to the number which could be performed on a daily basis. Previously, duplicates were conducted at 10 % and 15 % on consecutive days. It was desired to determine if the variability of the manure was significant to the difference in the results for the differing dosage. In this section of the work tests were conducted with the same raw manure and stabilized with 10 % and 15 % quicklime for the purpose of determining any differing effects on ammonia volatilization using the same manure over the one hour mixing period. Figure 4.28 shows the cumulative response to the different doses of quicklime.

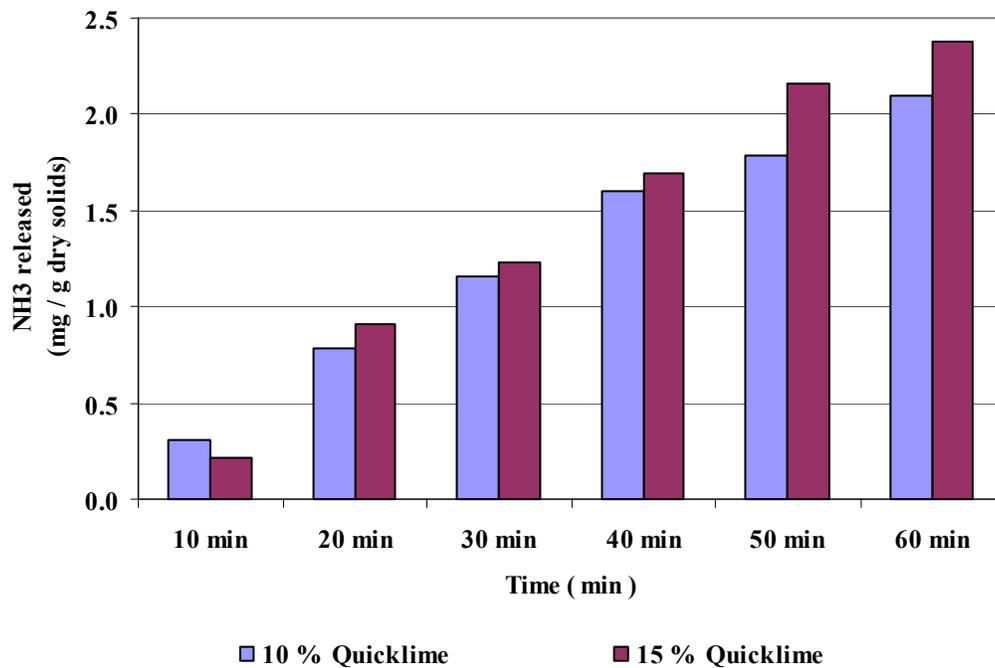


Figure 4.28. Ammonia volatilization for quicklime doses of 10% and 15% (Moisture content = 62%, Raw [NH₃] = 6.85 mg/g solids).

Initially, it can be seen that the 10 % dosed manure experienced greater volatilization of ammonia, however, by 20 minutes into the tests the 15 % quicklime had surpassed the

10 % dose in this respect. After the 60-minute period of mixing the 15 % dose had released more gaseous ammonia from the manure than the 10 % dose. These differences were small compared to those seen after modifying the mixing blade. This points to the idea that the blade is as much a factor in initial ammonia volatilization as the dosage difference between 10 % and 15 % quicklime.

Perhaps the 10 % dose dissolved more completely and reacted more readily with the manure. Figure 4.2 shows that the higher moisture manures experienced a faster pH change for the doses screened. This theory would however be an extrapolation as the moisture content for this manure is less than that used in earlier experiments.

Overall ammonia was reduced in the stabilized solids by 98 % to 99 % for all of the doses tested in Part 4.3. Only about 30 % of the ammonia reported lost by the mass balance between the raw manure and the product was captured during the 60 minutes of mixing. This suggests that either ammonia was lost after stabilization and before laboratory analysis or that ammonia had escaped the reactor unnoticed or adsorbed to the reactor/sample equipment.

4.4 Part 4 – Long Term Ammonia Volatilization

Further studies were required to determine the long-term volatilization of ammonia from the product during storage. The process was ran again in duplicate with 10% quicklime and ammonia-free air was used to constantly flush the reaction vessel for 28 days (Figure 4.29). Cumulative volatilization approached 12 mg/g dry manure solids after 28 days. Based on mass balance calculations, approximately 92.5% of the original

ammonia was lost after 28 days. Therefore, the mass balance results were more consistent with the storage data.

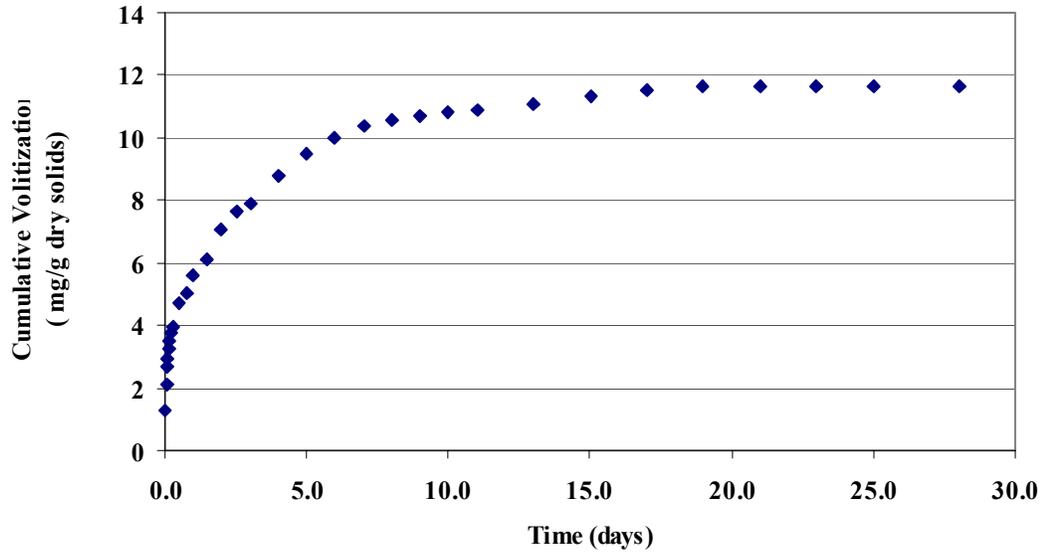


Figure 4.29. Ammonia volatilization at 10% quicklime over an extended period after mixing. Raw ammoniacal nitrogen = 12.78 mg / g dry solids.

The volatilization rate declined sharply after the 60-minute mixing period. The decrease in volatilization after 6 hours was likely due to the reduction of aqueous ammonia on the surface is quickly lost through rapid volatilization and is only slowly replaced by ammonia from within the manure matrix in the absence of mixing. This suggests that ammonia volatilization is limited by mass transfer without periodic mixing. Ammonia volatilization from the stabilized product was significant well after a mixing period of one hour. Therefore, periodic or intermittent mixing might be sufficient to maintain this volatilization rate.

It would be ideal to maintain the volatilization rate observed at the start of the reaction as long as possible for the most efficient removal of ammonia from the solids.

Thorough mixing allows for complete reaction of the reactants (manure and quicklime), mixing after this point allows evaporated ammonia on the surface of the manure to be continuously replaced. Therefore varying the mixing time and intensity will affect the volatilization rate of ammonia.

4.5 Part 5 - Steady State Auger Reactor

4.5.1 Airflow Rates and Ammonia Volatilization

The high volatilization of ammonia captured during mixing as compared to storage led to the conclusion that NH_3 volatilization measurements for the prototype reactor were necessary to make decisions about the value/cost of capture/utilization. Ammonia volatilization increased linearly with airflow rates through the reactor. Air flow rates of 0.35, 1.06, and 4.25 liters / s (0.6, 1.8, 6.6 air changes per minute, respectively) were tested initially in the steady-state auger reactor (Figure 4.30).

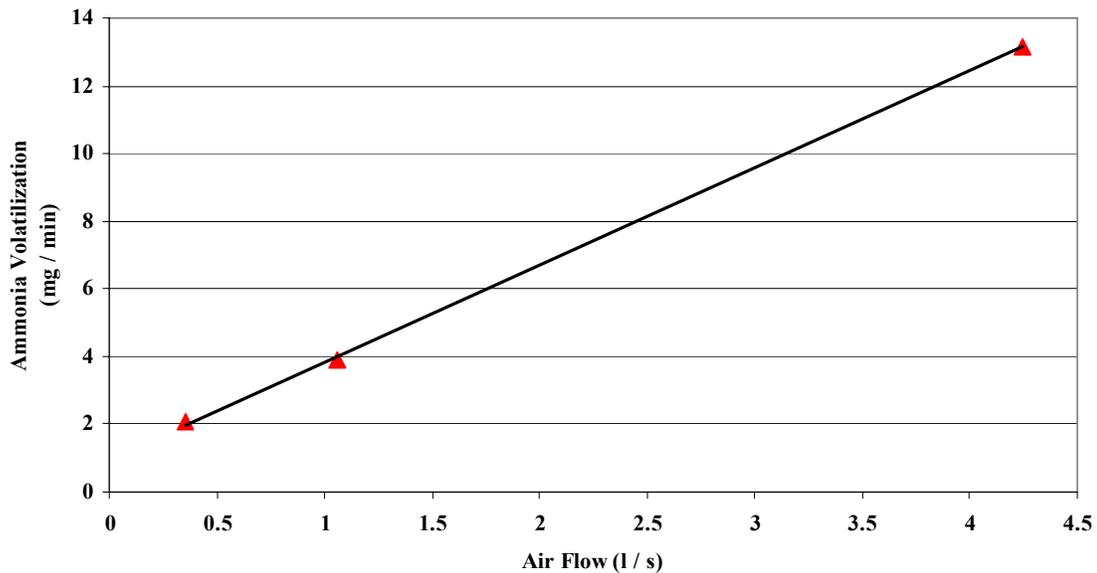


Figure 4.30. Ammonia capture for auger system using increasing airflow rates. Medium moisture content (63.8%), Quicklime dose = 10%.

A very linear increase in ammonia capture was observed for the auger when testing increasing airflow rates at this range. Air change ratios were varied from 0.6 to 6.6 air changes per minute. Noticing the increase in volatilization of ammonia with the increase in airflow rate, further tests were conducted at rates of 4.25, 5.66, and 7.08 l/s (6.6, 8.8, and 11.0 air changes per minute, respectively) (Figure 4.31). The later three trials were conducted with higher inlet manure temperatures (11⁰C as opposed to 7⁰C), higher moisture manure (76 % as opposed to 64 %), and a higher ammonia to solids ratio (12.9 as opposed to 7.3 mg ammoniacal nitrogen / gram dry solids). Higher moisture in the raw manure also resulted in higher reactor temperatures (8 degrees on average at T1, T2, and T3 along the reactor). The higher ammonia to solids ratio manure had a larger

portion of ammonia which may explain the larger volatilization rate and steeper curve for the second set of tests (Figure 4.31).

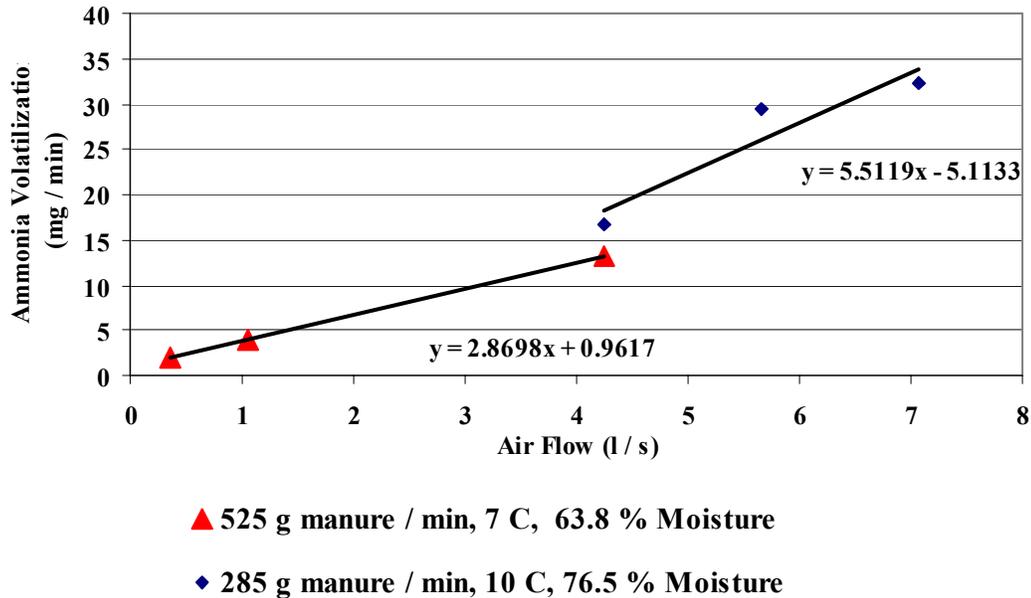


Figure 4.31. Ammonia volatilization for the auger system using varied airflow rates. High moisture content (76.5%), Quicklime dose = 10%.

Figure 4.31 illustrates that eventually the amount of ammonia, which may be removed by increasing the airflow, begins to decrease with respect to the proportion of air used to flush the annular space. To bring perspective to the issue of ammonia removal it should be added that only 0.1% of the original ammonia was removed per minute under the worst conditions (cold and dry manure at low quicklime doses) and 4% under the best conditions (warm moist manure at high quicklime doses). Ammonia constituted only 15-20 % of the total nitrogen in the solids, therefore only 1-2 % of the nitrogen could be removed by the auger reactor under the range of conditions tested. Therefore, significant nutrient recovery in the form of ammonia gas by the current auger vacuum system was

not feasible with the current auger design. Rather, slow vacuum of a shrouded airtight product container is recommended for further work on enhanced NH₃ recovery, with flow rates of just enough to prevent ammonia escape from the hopper inlet of the auger. The goal then shifts from recovery and reuse to pollution prevention.

4.5.2 Airflow and Temperature

As expected, increased airflow lowered reactor/reaction temperatures (Figure 3.32).

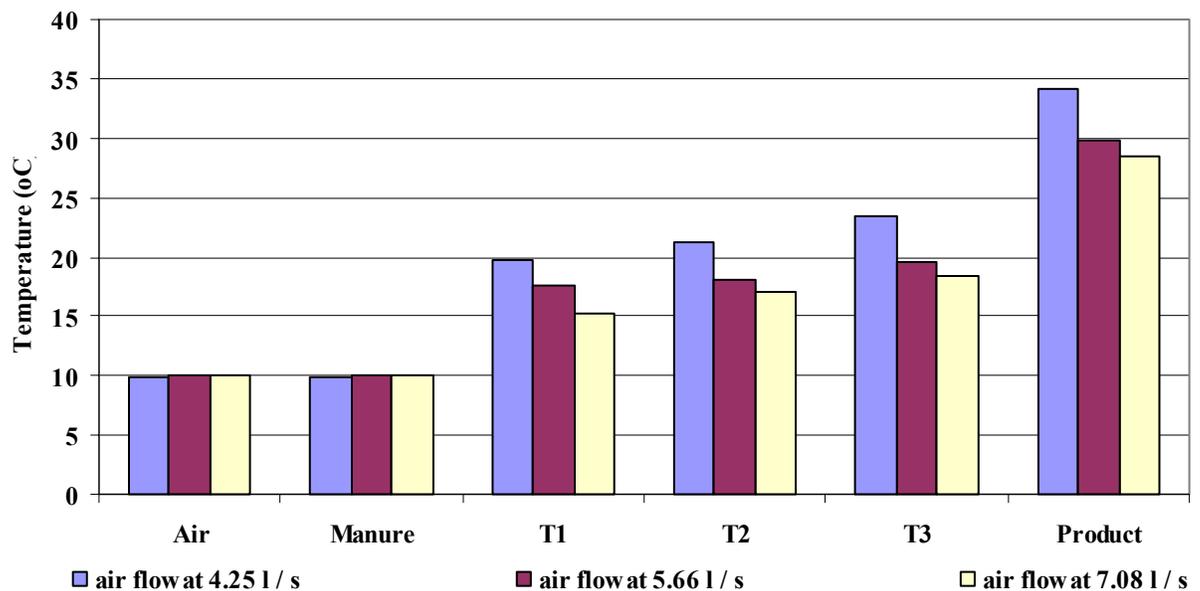


Figure 4.32. Temperature characteristics for auger using varied airflow rates. High moisture content (76.5%), Quicklime dose = 10%. T1-T3 represent temperatures from the three equally spaced thermocouples along the 4.57 meter reactor.

A slight increase in ambient air temperature occurred as the day of testing progressed. Likewise manure temperature increased slightly (0.5 °C / hour) due to the ambient condition and continual agitation within the dispenser. The airflow rate can be well correlated to the vessels temperature for this series of tests. The heat balance, given

later in Part 5, also reinforces the trend of increased heat removal by increased airflow through the reactor. This reduction in temperature, carried over to the stabilized product temperature, is quite undesirable. This is especially true when the product is not achieving the benchmark temperature set forth for Class-A biosolids.

4.5.3 Mixing Intensity and Temperature

In order to examine mixing intensity, the auger was operated at various angles (tilts). When the output end of the auger was raised auger speed was increased approximately 10 % for each 22.5^o increment maintain constant residence time for each trial. This allowed mixing intensity to be evaluated independent of residence time in the auger. For this set of trials the residence time was three minutes and fifty seconds, making the linear manure speed approximately 1.19 meters (3.9 feet / min) per minute.

Higher mixing intensities resulted in higher reaction temperatures (Figure 4.33). The increase in heat cannot be attributed simply to increased friction, as runs conducted without quicklime addition at these angles raised reactor temperatures by only a fraction of a degree. At the mid point of the auger, mixing with manure alone raised the temperature 0.33 ^oC when level, 0.66 ^oC when at 22.5 degrees, and 0.85 ^oC when operated at a 45 degree angle. T1, T2, and T3 in the figure represent the detected internal temperature of the reactor using the three equally spaced probes at 0.76, 2.28, and 3.81 meters along the 4.57 meter reactor.

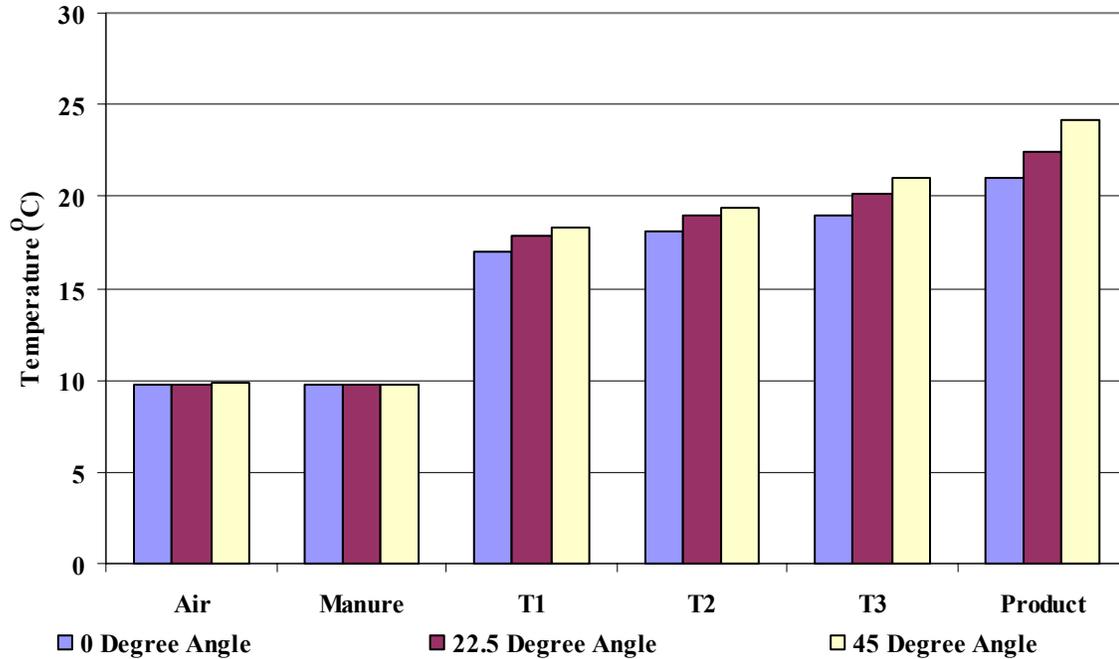


Figure 4.33. Temperature profile for auger using varied angles and speeds to vary mixing intensity. Medium moisture content (63.8%) airflow at 3 CFM, 10% Quicklime.

4.5.4 Mixing Intensity and Ammonia Volatilization

Angle of operation affected ammonia volatilization (Figure 4.34). The total amount of captured ammonia increased as the angle of operation was increased. However, the total amount of ammonia captured at the higher angle of operation was only 140 mg for the entire length of the reactor, which was 6 percent of the original ammoniacal nitrogen concentration and one percent of the total nitrogen. Therefore, mixing was as good with respect to NH_3 volatilization as the batch reactor if the smaller residence time of the auger is not considered.

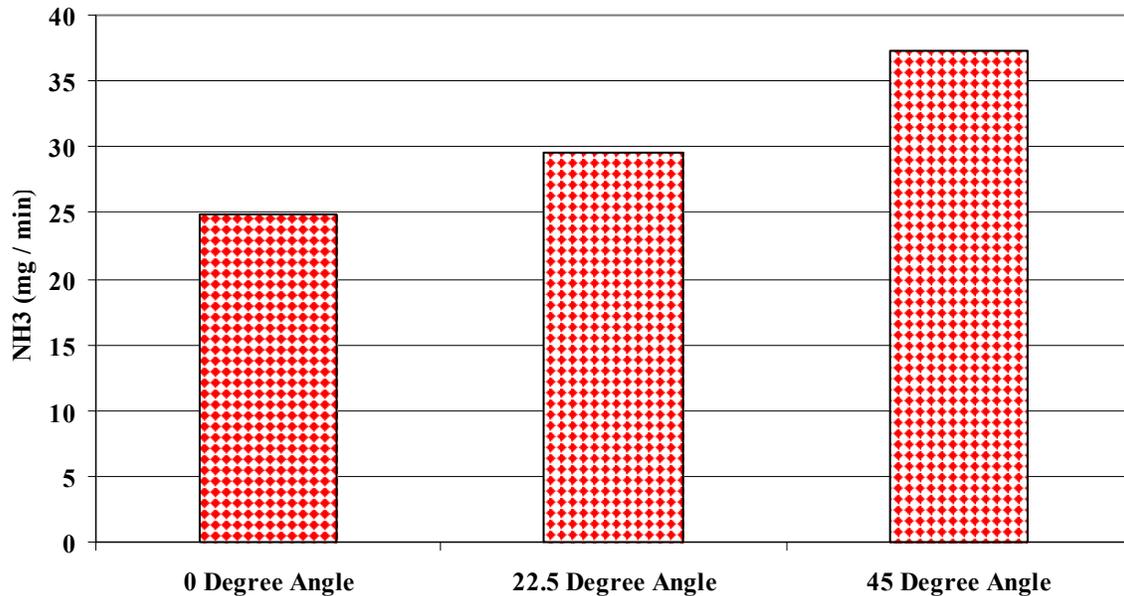


Figure 4.34. Ammonia volatilization for the auger reactor at varied angles and speeds of operation. Medium moisture content (63.8%) airflow at 3 cfm, 10% quicklime.

With greater intensity and angle, it is likely that the manure wetted surface area increases. Higher auger speeds also serve to create a larger turnover rate of the manure, refreshing the surface ammonia concentration with greater frequency. These two factors, combined with higher reaction temperatures, would explain the larger ammonia volatilization rate.

4.5.5 Moisture Content and Temperature

Due to the narrow moisture range tested Part 2, the range was extended for Part 5, 51.6 – 76.5, by changing operation of the belt. The highest moisture manure (76.5 %) was produced by using the maximum functional belt speed operated in a continuous fashion. The medium moisture manure was collected daily by intermittent operation on a

24-hour basis. The driest manure was produced by spreading the manure in a ½ inch layer and passing warm air rapidly over the surface for a 5 hour period, agitating occasionally.

Final product temperatures are important to satisfy the CFR 40 Class - biosolid treatment requirements. Figures 4.35 to 4.37 represents the air, manure, reactor, and product temperature for the high, medium, and low moisture manure when stabilized at quicklime doses of 10 %, 15 %, and 20 % respectively.

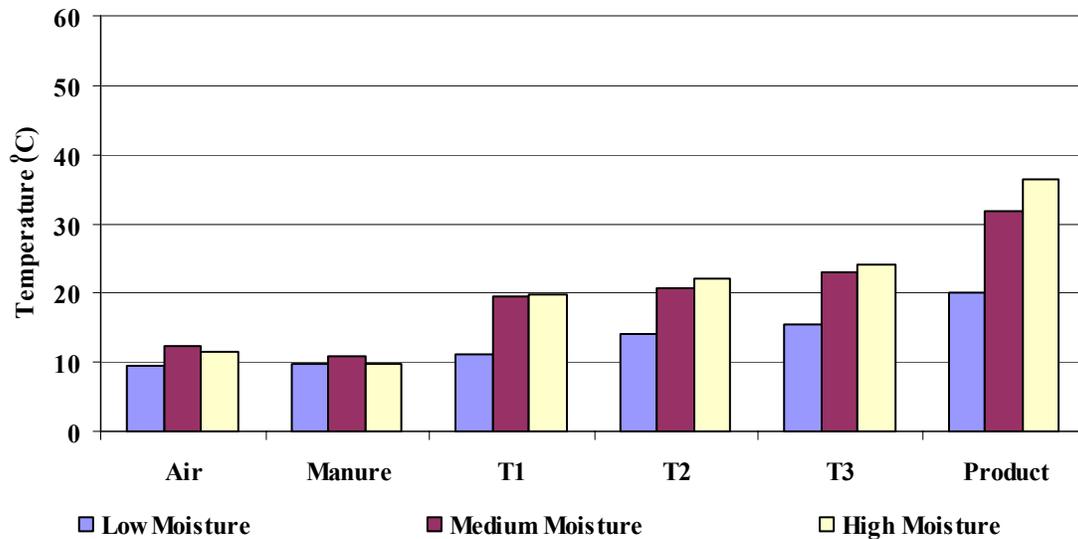


Figure 4.35. Stabilization temperature profile for quicklime doses of 10% on a wet weight basis. Low moisture content = 51.6%, medium moisture content = 63.8%, high moisture content = 76.5%. T1, T2, and T3 represent temperatures at 5-foot intervals along the reactor.

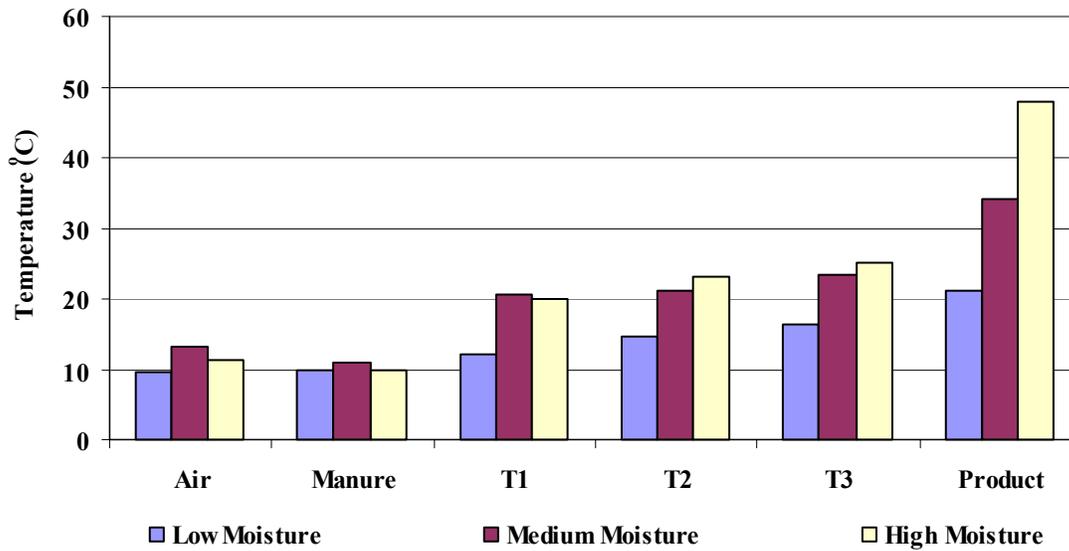


Figure 4.36. Stabilization temperature profile for quicklime doses of 15% on a wet weight basis. Low moisture content = 51.6%, medium moisture content = 63.8%, high moisture content = 76.5%. T1, T2, and T3 represent temperatures at 5-foot intervals along the reactor.

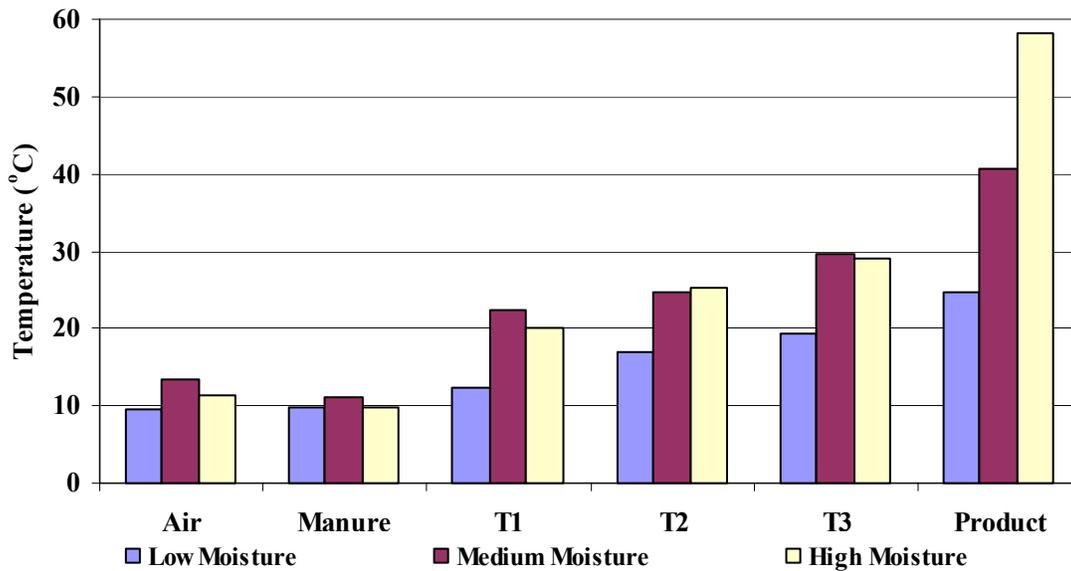


Figure 4.37. Stabilization temperature profile for quicklime doses of 20% on a wet weight basis. Low moisture content = 51.6%, medium moisture content = 63.8%, high moisture content = 76.5%. T1, T2, and T3 represent temperatures at 5-foot intervals along the reactor.

Higher manure moisture content resulted in higher reaction temperatures. This is a result of increased hydration due to a larger amount of available water for contact and reaction with introduced quicklime. Higher temperatures were also observed for higher doses of quicklime, which is similarly related as an increase in one of the hydration reactants.

Residence times varied significantly for the different moisture content manures. The medium moisture manure was in the auger the longest at an average of 314 seconds. Higher moisture manure was less viscous and eluted quicker with an average residence time of 250 seconds (25 % less time than medium moisture content). The dry manure did not adhere to the clean auger flights and eluted at the quickest rate of 165 seconds (50 % less time than medium moisture) in larger more rounded clumps.

The inlet temperature of the manure seemed significant as the temperature of the higher moisture manure lagged behind the medium moisture manure for the first few feet of the reactor. However, the temperatures were similar at 2.5 feet from the inlet of the auger, and by time the manure had traveled another five feet the stabilization temperature of the higher moisture manure had surpassed the manure with a lesser moisture content. Only the highest moisture manure combined with 20 % quicklime had a product temperature above the 50 °C requirement Class-A biosolids.

4.5.6 Moisture Content and Ammonia Volatilization

Figure 4.38 represents the increase in NH₃ volatilization for the stabilization manure with the higher range of moisture contents. The lowest moisture manure had a

very low volatilization rate, which changed only slightly with increased quicklime dose. As moisture content increased from 51.6 to 63.8 % ammonia volatilization increased five fold for a given quicklime dose. Further increase in moisture content to 76.5 % approximately doubled the volatilization rate showing that moisture is as important as dose for increasing ammonia volatilization.

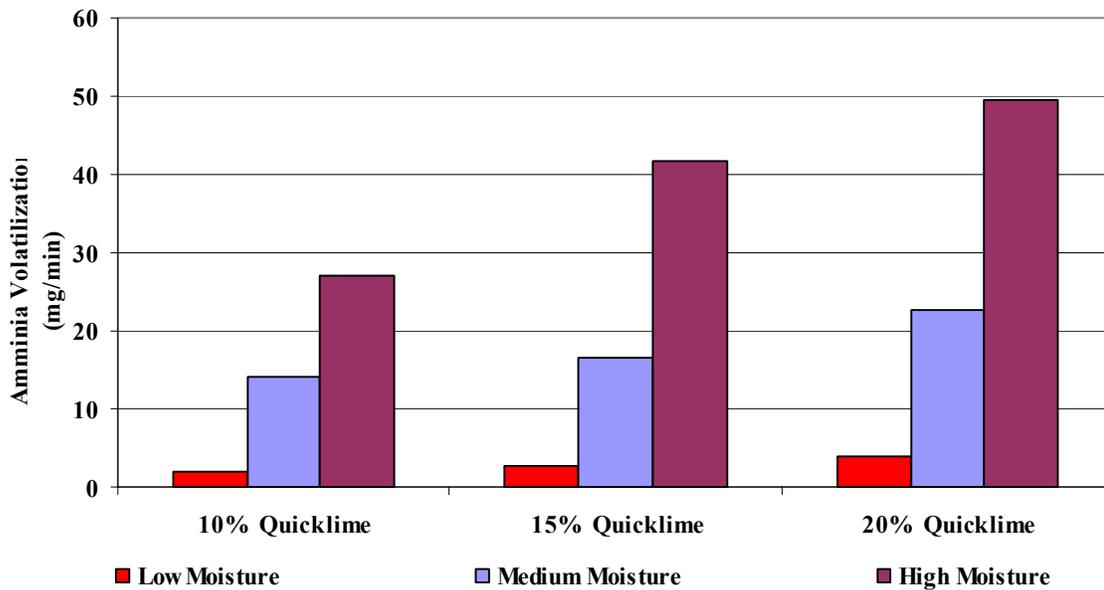


Figure 4.38. Ammonia capture for the auger system using 10, 15, and 20% Quicklime Doses. Moisture contents of 51.6 %, 63.8 %, and 76.5 % are shown. Airflow was set at 4.25 liters / s.

The increase in volatilization is likely due to the increased temperatures as observed for the higher moisture content trials. Another factor is perhaps the larger surface area covered by moist manure, as it was observed that the lower viscosity and higher moisture manure coated the auger blade more consistently than the dryer manure. It should also be added that the moist manure required a higher auger speed to achieve

similar residence times. This is indicative of increased mixing intensity. As presented in the previous section, increased mixing intensity results in larger volatilization rates.

4.5.7 Quicklime Dose and Temperature

Quicklime doses of 10 %, 15 %, and 20 % were screened at the range of moisture content described previously. Ammonia volatilization and temperature were examined for nine trials under these conditions. Figures 4.39-4.41 represent the air, manure, reactor, and product temperature for quicklime doses of 10 %, 15 %, and 20 % for high, medium, and low moisture manure respectively. Organizing the results in this manner resulted in similar trends observed in Figures 4.35-4.37. The main difference in the two interpretations is that inlet manure temperatures were the same for each data set presented below. This is due to the fact these tests were conducted on the same day, with the same manure.

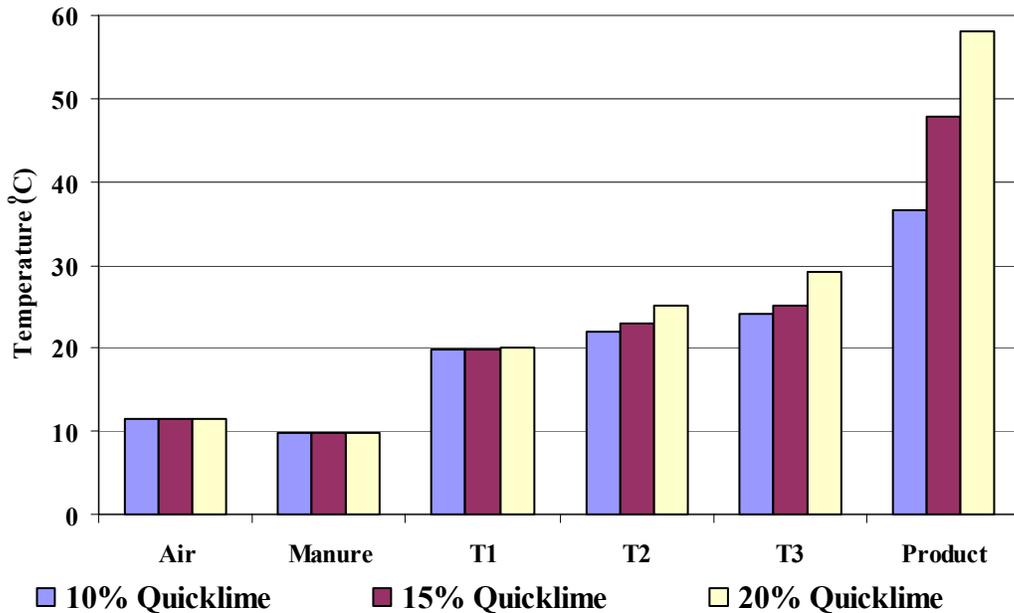


Figure 4.39. Temperature profile for auger using varied quicklime doses. High moisture content (76.5%), airflow set at 4.25 l / s. T1, T2, and T3 represent temperatures at 5-foot intervals along the reactor.

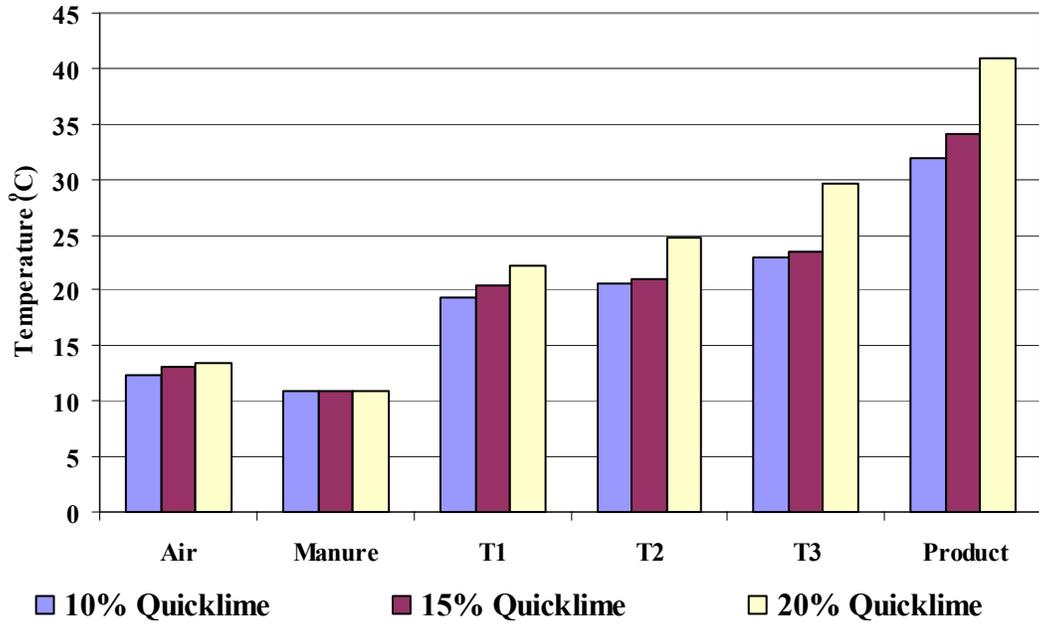


Figure 4.40. Temperature profile for Auger using varied quicklime doses. Medium moisture content (63.8%) air flow at 3 CFM. T1, T2, and T3 represent temperatures at 5-foot intervals along the reactor.

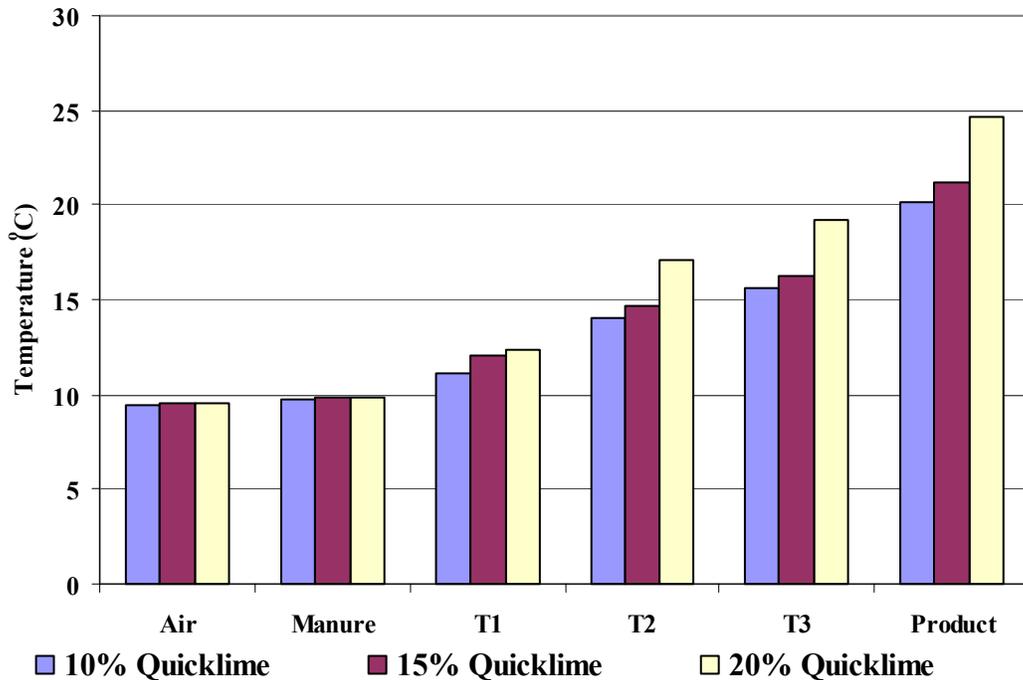


Figure 4.41. Temperature profile for auger using varied quicklime doses. Low moisture content (51.6%) airflow at 3 CFM. T1, T2, and T3 represent temperatures at 5-foot intervals along the reactor.

Temperature increased as the reaction proceeded. Again the product temperature increased slightly more than would be predicted by the linear trend exhibited while the manure was being stabilized in the reactor (Figures 4.39-4.41). Similarly this can be explained by the build up of mass and heat in the product container and perhaps inaccuracy in location and measurement of the exact slug of manure ejected in concordance with the timed regimen of the reactor. It is therefore suggested that storage containers be insulated and as large as possible to conserve heat and increase the product temperature.

Temperature responses to dosage increase provided evidence of the effect that quicklime ratios place on reaction temperature. At the halfway point through the reactor (T2) quicklime increases from 15 % to 20 % had a larger effect on temperature than the change from 10 % to 15 % quicklime. This trend held true for the final product temperatures as well, and seemed more exaggerated for the medium and high moisture manures. The data indicate that there could exist a breakpoint in temperature response to quicklime doses between 15 % and 20 %.

4.5.8 Quicklime Dose and Ammonia Volatilization

The previously presented Figure 4.35 addresses this issue. Increases in the percentage of quicklime added on a wet weight basis resulted in proportional and consistent increases in volatilized ammonia. The lime dose had a larger effect than did the MC over the ranges tested. Doubling the quicklime dose approximately doubled the rate at which ammonia was captured. However this rate was still insufficient to warrant capture for reuse.

4.5.9 Insulated Operation

After insulation of the reactor with two layers of reflective aluminum foil insulation with a 0.8 cm (0.31 inch) dead air space, three trials were conducted at the previously screened quicklime doses. The dashed lines in Figure 4.42, below, represent similar trials after the addition of two layers of insulation.

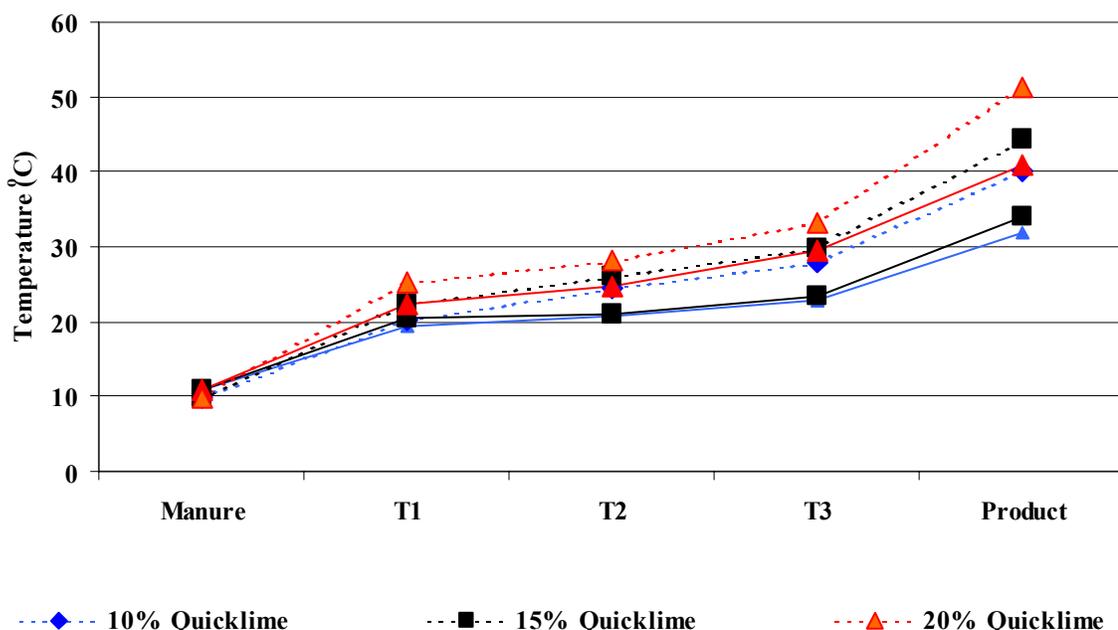


Figure 4.42. Matching trials with and without insulation of the auger reactor using the medium moisture content (63.8%) manure at quicklime doses of 10, 15, 20%. T1, T2, and T3 represent temperatures at 5-foot intervals along the reactor. Dashed lines represent the results form the insulated trials.

Even though inlet manure temperatures were 2 °C higher for the non-insulated trials, the reduction in convective heat loss allowed for higher reaction temperature for each given quicklime dose. Typically, the reaction temperature was 3 °C higher for the insulated reactor, however product temperature increases were 8 °C, 10 °C, and 12 °C for the 10 %, 15 %, and 20 % quicklime doses. The insulated operation of the auger

resulted in the first trial with the medium moisture content manure that reached the 50 °C benchmark temperature for Class-A solids. The higher moisture manure reached 50°C without the aid of an insulated reactor. Although the insulation resulted in higher reaction temperatures, treatment under warmer conditions combined with insulation of the reactor vessel is likely to have substantially higher temperature.

4.5.10 Manure Temperature

Several trials were conducted with manure heated before introduction to the auger system to determine the benefit, which might be gained by in-house treatment.

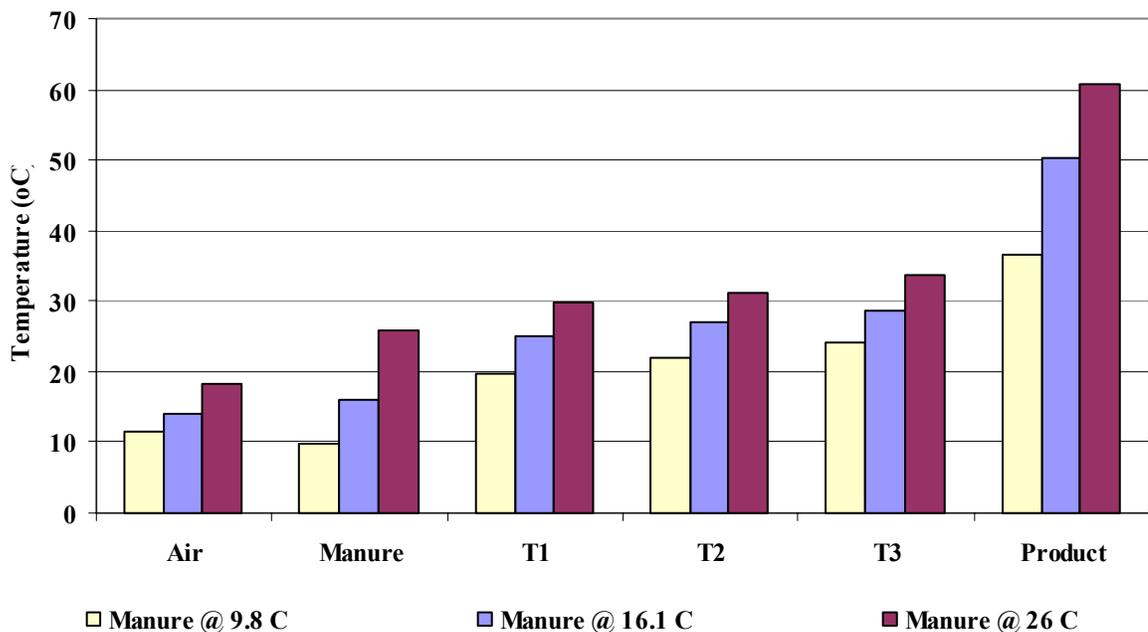


Figure 4.43. Temperature profile for the insulated auger using a range of raw manure temperatures. Medium moisture content (63.8%) air flow at 3 CFM. T1, T2, and T3 represent temperatures at 5-foot intervals along the reactor.

Reactor temperatures showed the highest increase 14-23 °C for the warmest manure. The hydration reaction therefore showed significant sensitivity to the temperature of the inlet manure. Tests with the heated manure and 15 to 20 % quicklime

were the only tests in which Class-A required temperatures (50 °C) were reached and maintained for the required twenty minutes under the conditions tested. Inlet manure temperatures below 16 °C did not result in the creation of a biosolid product meeting the requirements of a Class-A biosolid under the CFR40 even when dosed with 20 % quicklime on a wet weight basis.

4.5.11 Heat Balance

A heat balance around the reactor was performed in order to gauge the amount of quicklime hydrated as a function of time. This served to determine the rate at which quicklime was hydrated and the amount of quicklime remaining in stabilized product after exiting the auger reactor. Preliminary tests were conducted without quicklime to gauge mechanical heat added to the system. Heat added through the mechanical friction of mixing (0.5-2.2 J/s) was determined to be of several orders of magnitude less than other constituents of the heat balance.

The heat change of the air, manure, and calcium oxide that traveled through the reactor is considered a sink and therefore an overall loss for the system. This is calculated simply by determining the heat change of the individual components (heat capacity * ΔT * mass). Likewise, the amount of heat lost through natural convection is a significant sink for the system. The only significant gain of heat to the system is through calcium oxide hydration. Setting the losses or sinks equal to hydration heat and opposite in sign, the amount hydrated and ratio to the originally added calcium oxide were then calculated (Table 4.3).

Table 4.3. Heat balance totals for the auger stabilization reactor.

Run	Variable	Δ Heat Manure	Δ Heat CaO	Δ Heat Air	Convective Heat Loss	Water Volatilization Condensation	NH3 Volatilization	CaO Heat of Hydration	Hydration Efficiency
	Units	J / min	J / min	J / min	J / min	J / min	J / min	J / min	%/ min
11	airflow @ .75 CFM	-4491	-82	-158	-1122	-2764	-4	8623	13.98
12	airflow @ 2.25 CFM	-4250	-76	-432	-949	-2973	-8	8688	14.36
13	airflow @ 9 CFM	-4835	-87	-1565	-654	-2958	-26	10126	16.42
14	Dose 10% Med MC	-8939	-163	-3205	-1338	301	-28	13374	23.89
15	Dose 15% Med MC	-7563	-205	-3441	-1891	1953	-33	11182	13.16
15b	Dose 20% Med MC	-17282	-616	-4758	-2615	2757	-44	22560	20.15
16	mixing low	-5646	-102	-3106	-1297	-2950	-48	13149	21.48
17	mixing Med	-6175	-114	-3454	-1715	-2720	-58	14237	22.99
18	mixing high	-7636	-139	-3640	-1807	-3174	-73	16473	26.70
19	Mixing Jog	-14479	-268	-4150	-2060	-4948	-72	25977	41.25
20	Dose 10% High MC	-10345	-179	-3938	-1644	-7167	-53	23328	46.61
21	Dose 15% High MC	-12599	-329	-4199	-2085	-9477	-82	28771	37.97
22	Dose 20% High MC	-22307	-760	-5007	-2751	-14284	-98	45207	45.16
23	Air 9 CFM High MC	-5767	-99	-4311	-2141	-6030	-33	18381	55.61
24	Air 12 CFM High MC	-3376	-59	-4224	-1573	-9981	-58	19272	57.29
25	Air 15 CFM High MC	-5054	-89	-4369	-1095	-12613	-63	23283	67.81
26	Dup. of # 12	-7636	-192	-3591	-1783	-13330	-28	26559	54.33
27	Manure Temp	-5627	-102	-5504	-3980	-2451	-56	17720	50.92
28	Manure Temp	-6171	-109	-6138	-4770	-3143	-61	20391	59.39
29	Dose 10% Low MC	-1989	-39	-919	-384	4847	-4	512	1.43
30	Dose 15% Low MC	-6287	-183	-1814	-757	8424	-5	623	1.19
31	Dose 20% Low MC	-10298	-396	-2510	-1048	11082	-7	3178	4.55

4.5.12 Hydration Heat

Computed heats of quicklime hydration were greatest for the experiments conducted at the highest moisture content (45 kJ / min) or with elevated manure temperature (20 kJ / min). The small degree of heat lost through phase change of ammonia is insignificant in the heat balance. Hydration heat is of primary concern as it reflects on both the increase in pH and temperature of the manure which in turn manipulates the ammonia volatilization rate. Higher hydration heat indicates better performance of the stabilization unit due to a larger temperature increase per time or, equivalently, per linear foot traveled through a reactor by the manure undergoing stabilization. Hydration heat as a function of time is useful to the extent that the process depends on the heat derived from the hydration reaction. The pH requirement is met by the smallest quicklime doses (5 % quicklime in Part 2). Likewise, the heat needed to reach and maintain 50⁰C for 20 minutes is very dependent on the initial temperature of the manure and not significantly dependent on dose. Efforts should then be placed on limiting the cooling and loss of moisture from the manure for the most efficient hydration. This leads to the thought of reducing airflow to a minimum. This flow rate should be just large enough to prevent release of ammonia from the reactor body.

4.5.13 Hydration Efficiency

The efficiency of the hydration reaction is defined as the percentage of original calcium oxide (quicklime) that becomes hydrated in the reactor or the percentage hydrated as a function of time while within the reactor.

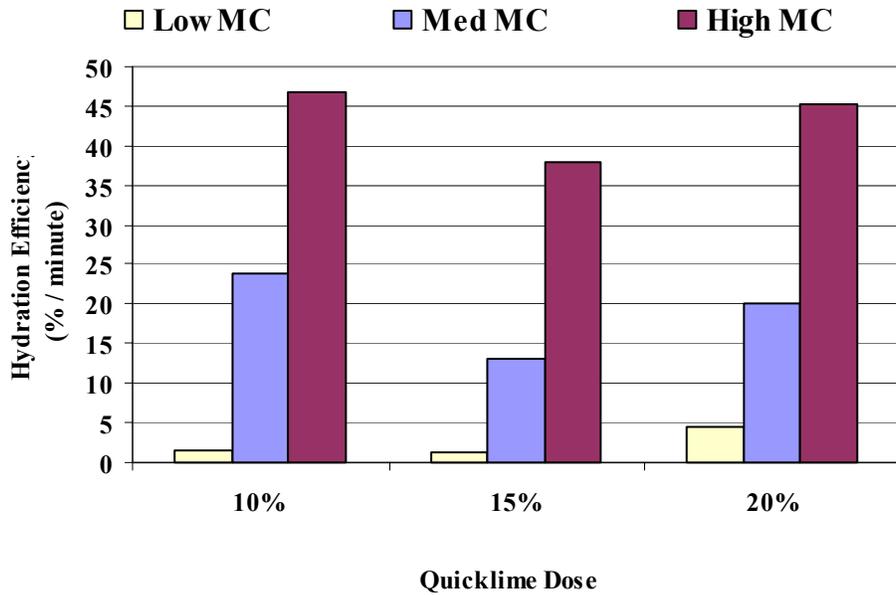


Figure 4.44. Percent of hydration accomplished per minute for a range of moisture contents screened against quicklime doses of 10, 15, and 20%.

Hydration efficiency of quicklime increased rapidly as moisture was increased. However, increases in dose did not increase efficiency (Figure 4.44). In fact, on average, dosage increases resulted on a slightly lower efficiency. This is logical due to the increased amount of quicklime added and the unchanging amount of reactant water in the manure. Quicklime hydration efficiency is important for reasons of cost and temperature increase. Lower efficiencies will obviously require more quicklime to achieve similar temperature responses than tests with higher hydration efficiencies as a smaller percentage is hydrated and less heat is evolved with respect to the amount added. From a materials standpoint, the efficiency should be maximized to conserve operational expenses. From a thermodynamic point of view, higher efficiencies or rates of hydration on a time basis equates to higher maximum reaction temperatures. In both instances, higher hydration efficiencies are beneficial to system operation and product formation. Alternatively, the amount of unreacted quicklime within the manure can be estimated in

order to leave a residual amount to continually reduce vector transfer of pathogens, retain a high pH, or allow for use as the stabilized solids as a liming agent for soils as well as a nutrient source for crops.

4.5.14 Batch Reactor

Near the end of the testing window, a 200 gallon (794 l) stainless steel ribbon mixer was used for screening the 10 %, 15 % and 20 % battery of quicklime doses on belt-separated manure. A series of batch tests were ran, and pH and temperature profiles were measured (Figures 4.45 and 4.46).

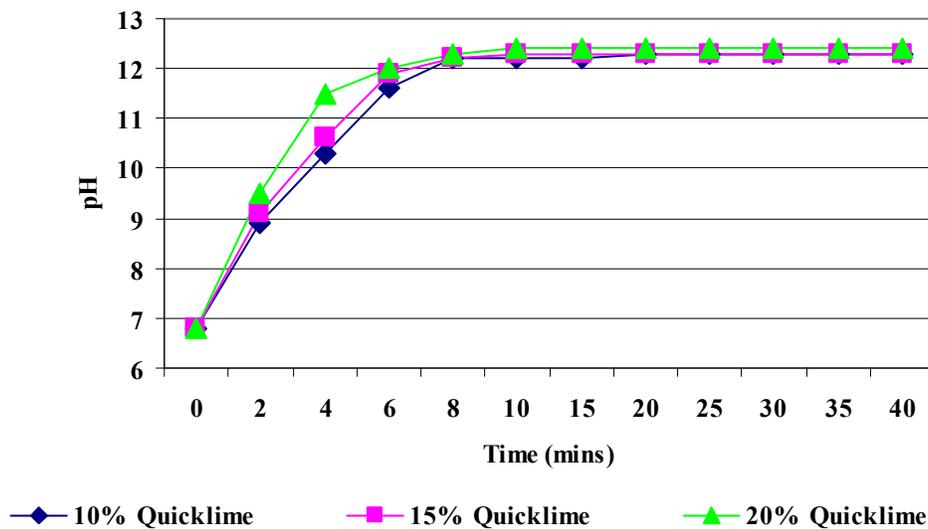


Figure 4.45. pH Profile as a Function of Quicklime Dose for a 200 gallon ribbon mixer.

The pH profiles were very similar to those presented for the 14-liter batch tests in Part 2. Lower doses had a slightly slower response to the addition of quicklime. The

final pH was the same for all the doses tested. Ammonia volatilization, as it is related to pH, is therefore not dependent on dose beyond the first few minutes of mixing.

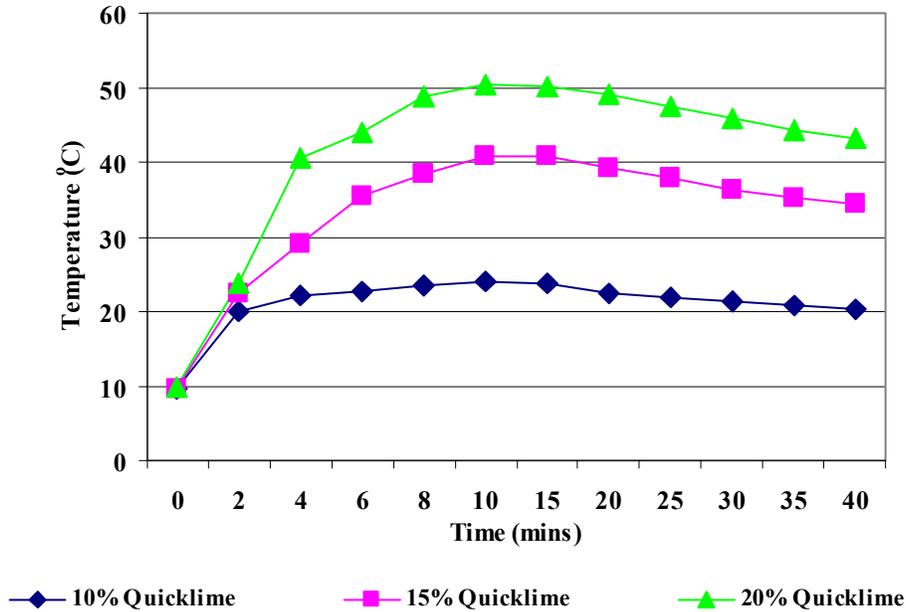


Figure 4.46. Temperature Profile as a Function of Quicklime Dose for a 200-gallon ribbon mixer. Moisture Content = 75.6%.

The temperature profiles were stratified according to dose. Again these results match the trends determined in Part 2, although the baseline was lower due to lower ambient and manure temperatures which were present for these three batch tests. The 20 % quicklime dosed batch broke the 50 °C benchmark but did not hold this temperature for the required 20-minute period.

Initial increase in quicklime dose from 10 % to 15 % resulted in a 12 °C increase after ten minutes of mixing. Further increase from 15 % to 20 % quicklime yielded a smaller temperature rise of only 5 °C. This indicates that further increases in quicklime dose are likely to have yet smaller temperature increases. This coincides with the view that water can become the limiting reactant as dosage is increased. During winter, when

viscosity is high, water is more closely tied to the manure and therefore less available for immediate reaction. To support this, the hydration efficiencies were on average highest for the warmest (26 °C) manure tested.

4.5.15 Statistical Analysis

Statistical Analysis System (SAS) was used for the analysis of covariance between the independent variables and the mathematical relation to the dependent variables. Selectively, each combination of variables was screened and by stepwise removal, independent variables whose significance was below the 80 % confidence and whose **Pr>t** was larger than 0.2 were removed. Each model section will include the respective **Pr>t** values for independent variables included in the given model. When reviewing these tables it is important to remember that lower **Pr>t** values are an indication of a higher significance to the relationship.

Mixing intensity was insignificant at the range tested and number of tests performed. It is likely that more confidence could be placed on its significance if a larger number of trials were performed with the manipulation of this variable alone. Similarly, the manure flow rate was not significantly related to any of the modeled variables indicating that the reaction temperature, ammonia volatilization, quicklime efficiency, and product moisture content were independent of manure flow rate over the range tested. Perhaps this is the range of manure flow tested was relatively small (281-529 g/min).

Model equations are given next for the prediction of product temperature, moisture content, ammonia volatilization, and hydration efficiency for the reactor. The model proposed for ammonia volatilization is on a dry solids basis and therefore a

function of the dry manure flow rate. Alternatively, hydration efficiency is presented on a per minute basis for use in controlling the amount remaining in the product at the time of ejection from the auger unit. Table 4.4 defines the variables used in the statistical analysis and regression.

Table 4.4. Independent and Dependent Variables used in SAS Analysis and Model.

Independent Variable			Dependent Variable		
	Abbr.	Units		Abbr.	Units
Manure Flow Rate	MF	g / min	Prod. Moisture Content	MCP	%
Quicklime Flow Rate	QF	g / min	Product Temperature	TP	0C
Raw Moisture Content	MCR	%			
Mixing Intensity	MX		NH ₃ Volatilization	AVS	ug/min/g dry solids
Raw Manure Temp	TM	⁰ C	Hydration Efficiency	HEM	% / min
Airflow	AF	ft ³ /min			

Product Moisture Content

Moisture content of the product was significantly related to the raw moisture content, quicklime dose, and air flow rate. The moisture content of the product for the prototype auger reactor may be predicted by the following equation.

$$MCP = 49.31 - 0.52 (QF) + 0.18 (MCR) - 0.28 (AF) \quad (4.2)$$

Table 4.5. Significance of model variables for prediction of stabilized product moisture content for the prototype reactor.

Variable	Product Moisture	Quicklime Flow Rate	Manure Moisture	Airflow Rate
Pr >:t:	Dep. Var.	0.0047	0.0172	0.1850

The moisture content of the product was determined not to be statistically related to the initial temperature of the manure solids, the flow rate of the solids, or mixing intensity. As expected, the airflow rate was inversely related. Higher airflows will reduce boundary layer thickness and increase volatilization of water from the surface of the stabilized solids. Likewise it is logical that the moisture content of the raw solids would directly influence the moisture content of the product. Similarly, it is logical that the quicklime dose is inversely related to product moisture content, as more contact with calcium oxide will result in greater hydration. Attaining a final moisture content below 50% has been demonstrated for doses as low as 5% and is apparently the easier of the CFR requirements for temperature, pH, and moisture content to obtain.

Product Temperature

Temperature of the stabilized manure was determined to be related to temperature and moisture content of the inlet manure as well as quicklime dose and airflow rate. The final temperature of the product from the auger reactor may be predicted by the Equation 4.3.

$$TP = - 62.83 + 1.77 (QF) + 0.80 (MCR) + 2.58 (TM) - 0.65 (AF) \quad (4.3)$$

Table 4.6. Significance of model variables for prediction of stabilized product temperature for the prototype reactor.

Variable	Product Temperature	Quicklime Flow Rate	Manure Moisture	Manure Temp	Airflow Rate
Pr >:t:	Dep. Var.	<0.0001	<0.0001	<0.0001	0.1321

Final product temperature was independent of the raw manure flow rate at this level of significance for the doses tested. Increasing airflow cools the reactor when ambient temperatures are below that inside the reactor. Again, in-house treatment is suggested for future incorporation of quicklime stabilization for reasons of higher manure temperature if external winter temperatures in the local area fall below 16 °C. The temperature, moisture content of the manure, and the quicklime flow rate had a larger significance in the prediction of product temperature as can be evidenced by extremely low Pr >:t: value for these independent variables.

Ammonia Volatilization

On a solids basis, ammonia volatilization was significantly and directly related to airflow, solids temperature, moisture content, and quicklime flow.

$$AVS = -960.79 + 6.88 (QF) + 12.25 (MCR) + 7.18 (TM) + 22.23 (AF) \quad (4.4)$$

Table 4.7. Significance of model variables for prediction of ammonia volatilization per minute for the prototype reactor.

Variable	Ammonia Volatilization	Quicklime Flow Rate	Manure Moisture	Manure Temp	Airflow Rate
Pr >:t:	Dep. Var.	0.1099	<0.0001	0.0793	0.0007

Airflow and manure moisture are most significantly related in the prediction of ammonia volatilization. Likewise the coefficient for airflow is large indicating a high sensitivity to this variable for the range of airflow rates tested. Airflow had a negative effect on product temperature and reaction temperatures as well. As expected higher

quicklime doses result in higher pH values and slightly larger ammonia volatilization for a given air flow rate, temperature, and moisture content.

As was stated previously, the amount of ammonia captured is not sufficient to warrant capture for reuse. However this relationship may be used to raise or lower ammonia volatilization to be compatible with reduction systems and other operational parameters.

Hydration Efficiency

The efficiency of the hydration reaction is defined as the percentage of original calcium oxide (quicklime) that becomes hydrated in the reactor or the percentage hydrated as a function of time while within the reactor. Hydration efficiency is of primary concern as it reflects on both the increase in both pH and temperature of the manure which in turn manipulates the ammonia volatilization rate. Higher efficiencies for the hydration of quicklime indicate better performance of the stabilization unit. Higher hydration efficiencies result in a larger temperature increase per time or, equivalently, per linear foot traveled through a reactor by the manure undergoing stabilization.

Mixing intensity or angle was insignificant at the level required for inclusion in the model. Conversely, it would seem that it should play an integral part in the hydration efficiency of the reactor. As previously stated, a larger number of tests performed while simply manipulating mixing intensity and at a greater range of intensities could place more significance on this factor. However, it will be necessary to create either a pugmill type reactor for greater range in intensity or develop a similar system capable of monitoring power input to the stirring mechanism. Using viscosity, temperature, reactor geometry, and the power input for the auger blade or paddles a value for mixing intensity

may then be assigned for each trial. Flow rate of the raw manure was also insignificant in the prediction of hydration efficiency. Perhaps this is due to a small range of flow rates tested (281 – 529 g / min) and comparative volume of the auger reactor to this range of flow rates. Equation 4.5 is the model for the prediction of hydration efficiency for the prototype reactor. This equation can be used in conjunction with residence time to determine the length required by the same geometry under the same condition to hypothetically approach complete hydration.

$$\text{HEM} = -107.43 - 0.65 (\text{QF}) + 1.66 (\text{MCR}) + 2.04 (\text{TM}) + 1.81 (\text{AF}) \quad (4.5)$$

Table 4.8. Significance of model variables for prediction of the calcium oxide hydration efficiency for the prototype reactor on a per minute basis.

Variable	Hydration Efficiency	Quicklime Flow	Manure Moisture	Manure Temp	Airflow Rate
Pr >:t:	Dep. Var.	0.1457	<0.0001	0.0001	0.037

Inlet manure moisture and temperature had the greatest significance in the prediction of hydration efficiency, however airflow had the largest coefficient. It is believed that this is due to the fact that the hydration efficiency data are produced from the heat balance for the prototype reactor. In this balance, the calculated heat lost by heating air as it passes through the auger are a large component of the total heat calculated to be offset by heat of hydration.

Hydration efficiencies as a function of time are useful to the extent that the application depends on the heat derived from the hydration reaction. The pH requirement is met by the smallest of doses (5% quicklime in Part 2). Likewise, the heat needed to reach and maintain 50⁰C for 20 minutes is very dependent on the initial temperature of

the manure and not significantly dependent on dose. Efforts should then be placed on limiting the cooling and loss of moisture from the manure for the most efficient hydration.

4.5.15 Statistical Analysis Summary

Relationships were determined through tests with the specific geometry and conditions described. Attempts to ascertain exact values for volatilization rates or production temperatures using other systems with various geometries based on the presented model equations are likely to be misleading. Similarly, predicted values for hydration efficiencies and ammonia volatilization rates are likely to be inaccurate when temperatures, moistures, quicklime doses, and manures outside of the ranges tested are used conjunctively with the auger system.

The model equations give insight into the functions of temperature, moisture content, and flow rate on the degree of hydration and amount of ammonia given off under the specified conditions. Further work to refine the stabilization procedure in conjunction with belt systems is needed.

The analysis confirms experimental and intuitive conclusions. Warmer environments will have on average a better hydration efficiency, a higher reaction temperature, increased ammonia volatilization, and a greater propensity for equivalently fulfilling the CFR Class A biosolid requirements.

Product temperature was the most difficult of the CFR requirements to fulfill in the tests conducted. Therefore, the most influential factor for manipulation of this dependent variable is of primary concern. Raw manure temperature again becomes the

focus for control of product temperature. Thermal conductivity may play a key role in this matter as it increases with temperature for the water within the manure, while the heat capacity declines with increasing temperature creating a more conducive environment for hydration. Heat can be transferred more efficiently as the baseline manure temperature is increased.

4.5.16 Direction for Future Studies

There is certainly much room for improvement to the prototype reactor used in this study. From the experiments performed, the ideal reactor should be insulated and as close to the swine unit and separation device as possible to conserve heat in the manure solids. The process would preferably be inside the housing unit to take advantage of heat generated for and produced by the swine. Higher moisture contents for the stabilization process resulted in higher product temperatures. Therefore, there is no need to guide the separation technique from the standpoint of lowering moisture in the product, if in fact separation proves to be to be beneficial to the stabilization process.

Significant nutrient recovery in the form of ammonia gas by the current auger vacuum system was not feasible with the current auger design. The goal then shifts from recovery and reuse to pollution prevention with the current design. Alternatively, a system with a small funneled entrance would reduce the flow rate required to contain the NH_3 gas. Similarly, a much larger residence time ($\gg 5$ min) would be required to significantly reduce the ammoniacal nitrogen concentration of the solids while in the reactor.

The air flow rates used in conjunction with this work were to determine maximum volatilization rates as opposed to maximum ammonia concentration in the exiting air. Rather, slow vacuum across a shrouded airtight product container is recommended for further work, as this will result in ammonia containment while achieving the highest NH_3 concentration possible for the air stream. The flow rate should be just enough to create negative pressure in the reactor and prevent ammonia escape from the hopper inlet of the auger. The location of the gas port should therefore be in the vicinity between the auger and the product container, on an airtight shroud above the container.

The human nose will be one of the best instruments in optimizing this flow rate for any reactor geometry, as ammonia is a strong odor and detectable at only 50 ppm. There are many areas of research which concentrate on NH_3 reduction using catalysts, scrubbers, and filters for air streams with relatively low NH_3 concentrations. The recycle or removal process chosen for further work should be based on low-flow NH_3 laden air streams.

The product container should be designed large enough for at least one weeks operation at maximum volumetric capacity and insulated to retain as much heat as possible. This will allow for the highest stabilized product temperatures. As previously suggested in Part 4, intermittent stirring may be key to refreshing surface ammonia after partial depletion through volatilization. It is important to remember that volatilization will eventually approach but not reach zero. Likewise, volatilization is proportional to the aqueous concentration of NH_3 and will therefore slow as the concentration of NH_3 declines.

5 CONCLUSIONS

- A stabilized solids meeting the CFR40 Part 503 Class-A standards for biosolids can be formed from the reaction of scraped or belt-separated solid swine manure and 10 % to 15 % quicklime when raw manure temperatures are at least 16 °C.
- Cold manure temperatures inhibit the hydration of CaO from manure moisture.
- Batch and steady state trials showed a direct but limited relationship between quicklime dose and maximum product temperature.
- Ammonia volatilization was greater for higher temperatures and at higher airflow rates when pH values are 12 or higher and 99.9 % of total ammoniacal nitrogen is in the ammonia form.
- Capture of volatile ammonia from the process for the purpose of reuse or total nitrogen reduction is unwarranted as the maximum amount removed from the process was only 4 % of the total ammoniacal nitrogen and less than 1 % of the total nitrogen in the solids portion of the belt separated swine waste.
- At the bench scale, ammonia volatilization from the stabilized product declined drastically approximately six hours after a one-hour mixing period ended.

In Part 2 the reaction of scraped or belt-separated solid swine manure and 10 % to 15 % quicklime produced a stabilized product meeting the same requirements as Class-A biosolids defined by the CFR 40. Increased quicklime doses resulted in higher stabilization temperatures, faster initial pH increases during mixing, and lower residual moisture in the stabilized product. Ammonia was driven off at a slightly greater rate during the auger and batch experiments using the 15 % quicklime dose as opposed to 10 %. The difference in volatilization is likely not a direct effect of dosage but rather a secondary consequence of higher stabilization temperature for the greater dose. Part 2 also demonstrated that Class-A biosolid regulations were met by the 10 % and 15 % quicklime doses. Drying the product to 50 % solids is attainable by 5 % quicklime doses however heat generated at a batch scale of 14 kg for this dose did not meet temperature requirements under the CFR40 when ambient temperature were below 16 °C. The pH requirement of 12 after 72 hours was also not met by the 5 % quicklime dose. It is therefore recommended to dose at least 10 % for a stable solids product in summer conditions (> 25 °C) and 15 % or higher for ambient and manure temperature below 16 °C.

Part 3 demonstrated that volatilization differences among the 10 % and 15 % doses were small, and led to a focus on 10 % quicklime dosing for long term analysis. In the initial small-scale experiment, the rate at which the ammonia was volatilized (35-40 µg/g dry solids/min) was fairly constant for each of the ten-minute intervals of the mixing period. Likewise, an average ammonia volatilization rate of 42 µg /g dry solids/min was seen during the 60 minutes of mixing in long-term (28 day) experiment in Part 4. If this rate could be maintained it is possible to remove all the ammonia from the product in less

than five hours at the reaction temperatures experienced thus far. Gaseous escape of ammonia is an issue, which may be of environmental concern. Low flow rates of air drawn from the product end just fast enough to prevent ammonia from escaping the hopper inlet would be most appropriate for contact through natural or artificial filters or catalysts.

However, diffusion of the ammonia through the solids will limit this rate after mixing and the wetted surface ammonia has changed phase. Diffusion through the solid manure is temperature and moisture limited. As hydration of calcium oxide to calcium hydroxide continues and evaporation occurs, less water will be available for transport as the product begins to cool. Porosity in the stabilized product is likely to increase and aid volatilization somewhat. Although, the long term volatilization tests in Part 3 indicate that the rate at which ammonia is released decreases from 3.7 mg / min in the first 30 minutes after mixing to less than 0.7 mg / min at two hours post mixing.

Acceptance of new stabilization technology may hinge on the ability to demonstrate a prototype reactor, which can process the belt-separated manure in an environmentally and economically efficient manner. In Part 5, the construction and operation of the prototype reactor allowed for the thermodynamic and statistical analysis of the process with respect to important independent factors, which may be manipulated to refine the technique. Basic system parameters, such as moisture content and auger speed, were defined by trial and error. In so doing, a basic understanding of what will work and what will not work can be gained with respect to clogging, consistency and product form.

Statistical relationships showed that raw manure temperature, moisture content, quicklime dose, and airflow rate can be used to manipulate product temperature, moisture content, ammonia volatilization, and hydration efficiency. Finally, an economic analysis of materials cost was conducted. Assuming a delivered cost of \$ 100 per ton for quicklime and an average solids output by a comparative belt system of two pounds of solids per pig per day, the cost of quicklime for operation at the maximum dose tested (20 %) per day is approximately two cents per pig per day or 60 cents per pig per month. With more efficiency at higher temperatures, such as in-house treatment, 10 % doses would be sufficient for stabilization requirements which cuts the quicklime cost to one cent per pig per day.

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7 Appendix

Table 7.1. Abbreviations and acronyms.

Variable	Units	Definition
EPA		Environmental Protection Agency
OSHA		Occupational Safety and Health Administration
CFR		Certified Federal Register
MPN	# viable cells / g	Most Probable Number
PPM		Parts per million
PSRP		Process to significantly reduce pathogens
PFRP		Process to further reduce pathogens
$\Delta H_{\text{Hydration}}$	J/s	Heat of hydration for CaO
$\Delta H_{\text{Condensation}}$	J/s	Heat of condensation for H ₂ O
$\Delta H_{\text{Volatilization x}}$	J/s	Heat of volatilization for component x (H ₂ O or NH ₃)
ΔH_{manure}	J/s	Change in heat for manure
ΔH_{CaO}	J/s	Change in Heat for CaO
ΔH_{air}	J/s	Change in heat for air
$\Delta H_{\text{Volatilization x}}$	(J/mol)/ s	Heat of volatilization for component x (H ₂ O or NH ₃) per mol
MF	g/s	Mass flow (Manure, CaO, H ₂ O)
f_m		Volumetric fraction for mineral component
f_w		Volumetric fraction for water component
f_o		Volumetric fraction for organic component
C_{p_x}	J / K	Heat Capacity for Component x (H ₂ O, Manure, air)
L	m	Pipe length
D	m	Pipe diameter (outside)
r	m	Pipe radius (outside)
T_{in}	K	Air temperature in
T_{out}	K	Air Temperature out
T_{pipe}	K	Average external pipe temperature
T_{ambient}	K	Average ambient air temperature
AF	ft ³ /min	Airflow
HEM	% / min	Hydration efficiency
AVS	ug/min/g dry solids	Ammonia volatilization - solids basis
MX		Mixing intensity
QF	g/min	Quicklime flow rate
TM	⁰ C	Raw manure temperature
TP	⁰ C	Stabilized product temperature
MCR	%	Raw manure moisture content
MCP	%	Stabilized manure moisture content
MF	g/min	Raw manure flow rate

Part II April-August 2002		16 Liter Tests										
Moisture	Lower Moisture			Med Moisture				Higher moisture				Raw
Lime	5%	10%	15%	Raw	5%	10%	15%	Raw	5%	10%	15%	Raw
Code	1-1	1-2	1-3	1-4	2-1	2-2	2-3	2-4	3-1	3-2	3-3	3-4
Time	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C
0	27.8	28.3	28.9	27.8	33.3	33.3	33.9	33.3	32.2	32.2	32.8	32.2
2	30.0	37.5	45.6		37.2	40.0	53.3		42.2	44.4	52.2	
4	38.1	42.2	58.9		41.1	45.0	67.8		46.7	53.3	62.2	
6	42.2	46.9	65.0		43.3	53.9	68.3		48.3	60.0	75.6	
8	43.3	48.3	69.4		43.6	55.6	70.6		49.4	60.6	77.8	
10	43.9	51.7	72.2		44.4	57.2	73.9		49.4	60.8	78.3	
12	43.9	53.3	75.6		45.6	58.9	76.1		49.2	60.6	79.4	
14	43.9	53.6	76.7		46.1	60.0	77.2		49.2	60.6	81.1	
16	44.4	53.6	78.9		46.4	58.9	77.8		48.9	60.6	81.7	
18	45.0	53.9	81.7		46.4	57.8	78.3		48.9	60.6	82.2	
20	45.6	54.4	82.2		46.7	57.2	78.3		48.9	60.6	81.1	
22	45.8	55.3	80.0		46.4	56.4	78.3		48.9	60.6	80.6	
24	46.1	55.8	77.8		46.1	55.6	78.1		48.9	60.6	79.4	
26	46.1	55.6	77.8		45.8	55.0	78.1		48.6	60.6	78.3	
28	45.8	55.0	77.8		45.6	55.0	77.8		48.6	60.3	77.5	
30	45.6	54.4	77.8		45.0	54.4	77.2		48.6	60.3	76.7	
32	45.0	53.9	78.3		44.4	54.2	76.7		48.3	60.3	75.6	
34	45.0	53.6	78.6		44.4	53.9	76.4		48.3	60.3	74.4	
36	45.0	53.3	78.1		43.9	53.6	76.1		48.3	60.3	74.2	
38	44.7	53.3	77.8		43.6	53.3	75.8		48.3	60.0	74.2	
40	44.7	53.1	77.5		43.3	53.3	75.6		48.1	60.0	73.9	
Avg	42.9	50.8	72.2		43.9	53.5	72.6		47.5	58.0	73.8	

Part II 16 Liter Scale pH 40 Hour Post Test												
Moisture	Lower Moisture				Med Moisture				Higher moisture			
Lime Code	5%	10%	15%	Raw	5%	10%	15%	Raw	5%	10%	15%	Raw
Time(min)	1-1	1-2	1-3	1-4	2-1	2-2	2-3	2-4	3-1	3-2	3-3	3-4
	pH	pH	pH	pH	pH	pH	pH	pH	pH	pH	pH	pH
0	7.03	7.31	7.1	7.21	6.85	7.01	7.21	6.99	7.43	7.18	7.31	7.22
2	9.42	10.5	11.5		8.21	9.22	10.66		9.16	10.35	10.61	
4	9.86	11.4	12.48		10.82	11.01	12.57		12.72	12.46	12.51	
6	11.4	12.37	12.6		12.35	11.57	12.63		12.79	12.71	12.85	
8	11.9	12.45	12.62		12.6	12.2	12.7		12.78	12.74	12.87	
10	12.16	12.49	12.65		12.66	12.6	12.67		12.81	12.72	12.81	
12	12.15	12.57	12.68		12.64	12.65	12.68		12.87	12.71	12.87	
14	12.25	12.62	12.65		12.65	12.66	12.68		12.83	12.72	12.89	
16	12.42	12.65	12.61		12.6	12.7	12.7		12.81	12.69	12.89	
18	12.42	12.64	12.58		12.62	12.73	12.64		12.8	12.67	12.87	
20	12.41	12.64	12.58		12.63	12.77	12.61		12.79	12.67	12.88	
22	12.42	12.62	12.53		12.67	12.71	12.6		12.76	12.66	12.87	
24	12.45	12.6	12.46		12.65	12.68	12.6		12.76	12.67	12.81	
26	12.49	12.57	12.45		12.66	12.71	12.61		12.75	12.65	12.77	
28	12.5	12.53	12.48		12.65	12.76	12.59		12.76	12.69	12.75	
30	12.48	12.55	12.47		12.65	12.69	12.57		12.75	12.67	12.77	
32	12.5	12.61	12.5		12.64	12.71	12.59		12.73	12.66	12.71	
34	12.5	12.59	12.49		12.65	12.71	12.63		12.71	12.65	12.68	
36	12.48	12.58	12.49		12.63	12.72	12.65		12.7	12.65	12.69	
38	12.47	12.55	12.51		12.61	12.71	12.64		12.72	12.66	12.68	
40	12.45	12.56	12.49		12.61	12.71	12.63		12.72	12.65	12.67	
Avg	11.8	12.2	12.2		12.1	12.1	12.3		12.3	12.3	12.4	

Part II	16 Liter Scale		pH 40-168 Hour Post Test						
Hrs									
12	12.48	12.45	12.55	12.42	12.65	12.51	12.70	12.60	12.66
24	12.39	12.47	12.57	12.33	12.61	12.57	12.69	12.51	12.71
36	12.06	12.44	12.51	12.21	12.55	12.61	12.71	12.57	12.65
48	12.17	12.12	12.57	11.71	12.41	12.59	12.65	12.51	12.61
60	12.12	12.08	12.49	11.55	12.45	12.57	12.61	12.59	12.62
72	11.87	11.99	12.45	11.71	12.09	12.71	12.55	12.31	12.65
84	11.65	12.01	12.47	11.41	11.99	12.60	12.57	12.45	12.61
96	11.65	11.81	11.99	11.31	11.90	12.64	12.56	12.43	12.57
108	11.31	11.68	12.14	10.94	12.12	12.31	12.51	12.47	12.51
120	11.07	11.38	12.01	11.01	11.82	12.55	12.40	12.50	12.55
132	10.65	11.41	11.67	10.84	11.75	12.61	12.41	12.51	12.49
144	10.41	11.35	11.41	10.81	11.61	12.60	12.40	11.90	12.36
156	10.48	11.21	11.09	11.31	11.89	12.70	12.60	11.71	12.59
168	10.21	11.14	11.03	11.86	11.94	12.6	12.40	12.1	12.11

Part II Moisture Lime Code Time	16 Liter Scale			Residual Moisture								
	Lower Moisture			Raw Raw Raw	Med Moisture			Raw Raw Raw	Higher moisture			Raw Raw Raw
5%	10%	15%	5%		10%	15%	5%		10%	15%		
1-1	1-2	1-3	2-1	2-2	2-3	3-1	3-2	3-3				
Week 0	67.04	53.87	46.21	68.28	63.5	59.02	52.69	69.95	66.15	61.8	55.7	71.92
Week 1	42.68	17.67	32.26		44.05	46.03	42.68		44.05	40.56	26.03	
Week 2	13.66	31.12	34.63		35.17	44.92	31.38		20.46	29.82	31.04	
Week 3	11.11	13.15	19.04		10.83	32.79	19.35		22.5	22.21	9	
Week 4	10.15	3.62	10.71		8.7	18.41	8.95		8.67	24.68	13.12	
Week 5	15.56	11.89	12.85		11.67	12.2	25.77		10.93	13.48	4.33	
Week 6	10.99	9.37	9.24		10.65	12.49	12.41		10.1	11.59	10.3	
Week 7	13.89	12.52	10.85		11.88	13.16	20.36		20.68	12.36	9.35	
Week 8	10.51	10.01	9.26		10.07	9.73	8.15		9.67	13.96	7.72	

Part II		16 Liter Scale				Microbial Reduction							
Moisture		Lower Moisture				Med Moisture				Higher moisture			
Lime	5%	10%	15%	Raw	5%	10%	15%	Raw	5%	10%	15%	Raw	
Code	1-1	1-2	1-3	1-4	2-1	2-2	2-3	2-4	3-1	3-2	3-3	3-4	
Week	MPN / g	MPN / g	MPN / g	MPN / g	MPN / g	MPN / g	MPN / g	MPN / g	MPN / g	MPN / g	MPN / g	Raw	
Coliform	post test	8.00E+08	<4.0E+8	<4.0E+8	>4.8E+12	1.40E+04	2.00E+03	<2.0E+03	1.08E+13	<4.0E+03	<4.0E+03	1.00E+04	8.60E+11
	1	4.27E+03	<4.69E+03	<4.0E+03		1.49E+04	4.2E+04	1.8E+04		<4.98E+03	<4.42E+03	<5.25E+03	
	2	<4E+03	<4.81E+03	<4E+03		5.53E+06	<5.38E+04	<4.0E+03		5.33E+06	<4.73E+03	<4.25E+03	
	3	2.07E+05	<4.73E+03	<4.0E+03		>4.8E+6	<4.0E+03	<4.0E+03		<4.0E+03	<4.0E+03	<4.0E+03	
	4	4.64E+04	<4.0E+3	<4.0E+3		>4.8E+8	<4.0E+03	<4.0E+03		6.60E+06	<4.0E+03	<4.0E+03	
	5	7.43E+06	<4.3E+03	<4.52E+04		>=5.45E+09	<4.42E+03	<4.98E+03		4.6E+04	<4.0E+03	<4.0E+03	
	6	1.05E+07	<4.0E+03	<4.0E+03		<4.0E+08	>/4.8E+07	>6.25E07		4.60E+04	<4.0E+03	<4.51E+03	
	7	5.50E+05	<2.0E+03	<2.0E+03		1.00E+08	1.04E.04	<2000		>/=4.84E+05	<2.0E+03	<2.0E+03	
	8	4.02E+04	<2.0E+04	<2.0E+04		8.01E+05	1.10E+07	<2.0E+03		>4.83E+05	<2.0E+02	<2.0E+02	

Part II		16 Liter Scale				Microbial Reduction							
Moisture		Lower Moisture				Med Moisture				Higher moisture			
Lime	5%	10%	15%	Raw	5%	10%	15%	Raw	5%	10%	15%	Raw	
Code	1-1	1-2	1-3	1-4	2-1	2-2	2-3	2-4	3-1	3-2	3-3	3-4	
Week	MPN / g	MPN / g	MPN / g	MPN / g	MPN / g	MPN / g	MPN / g	MPN / g	MPN / g	MPN / g	MPN / g	Raw	
E. coli	1	8.00E+08	<4.0E+8	<4.0E+8	>4.8E+12	1.40E+04	2.00E+03	<2.0E+03	4.40E+12	<4.0E+03	<4.0E+03	<4.0E+03	6.60E+11
	2	<4.27E+03	<4.69E+03	<4.0E+03		1.49E+04	4.2E+04	1.8E+04		<4.98E+03	<4.42E+03	<5.25E+03	
	3	<4E+03	<4.81E+03	<4E+03		1.98E+05	<5.38E+04	<4.0E+03		<6.27E+03	<4.73E+03	<4.25E+03	
	4	6.02E+04	<4.73E+03	<4.0E+03		>4.8E+06	<4.0E+03	<4.0E+03		<4.0E+03	<4.0E+03	<4.0E+03	
	5	<4.03E+03	<4.0E+03	<4.0E+03		1.08E+08	<4.0E+03	<4.0E+03		6.60E+06	<4.0E+03	<4.0E+03	
	6	5.1E+06	<4.3E+03	<4.52E+04		3.6E+09	<4.42E+03	<4.98E+03		<4.0E+03	<4.0E+03	<4.0E+03	
	7	1.05E+07	<4.0E+03	<4.0E+03		<4.0E+08	>/4.8E+07	>6.25E07		4.00E+04	<4.0E+03	<4.51E+03	
	8	5.50E+05	<2.0E+03	<2.0E+03		2.44E+07	1.04E.04	<2000		<2.0E+03	<2.0E+03	<2.0E+03	
	9	2.01E+04	<2.0E+04	<2.0E+04		2.69E+05	1.10E+07	<2.0E+03		2.00E+02	<2.0E+02	<2.0E+02	

Part II Moisture Lime Code Time(Days)	Ammonia Reduction				NH3 in ug/g			as is	Higher moisture			
	Lower Moisture				Med Moisture				Higher moisture			
	5% 1-1	10% 1-2	15% 1-3	1-4 Raw	5% 2-1	10% 2-2	15% 2-3		2-4 Raw	5% 3-1	10% 3-2	15% 3-3
Post Test	279	295	288	1150	50.7	35.9	46.7	1064	44	70	53.6	790
1	19.8	20	30.2		15.3	13.6	22.2		23.2	33.8	22.3	
2	31.81	31.63	32.48		54.59	24.3	30.5		19.25	30.55	25.29	
3	34.27	27.81	30.51		106.16	21.43	22.1		21.79	32.32	21.22	
4	40.5	15.52	26.1		56.6	12	15.7		3.47	28.01	1.53	
5	41.3	17.5	28		71.6	10.74	33.6		19.8	21.5	11.3	
6	34.1	18.9	30.9		45.6	14.2	15.8		16.9	10.5	12.6	
7	79.2	21.3	36.4		76.2	23.3	17.8		55.9	20.8	18.9	
8	91	22.2	31.7		39.1	31.3	13.4		118.8	37.2	20.6	

Part II Moisture Lime Code Time(Days)	Ammonia Reduction				NH3 in ug/g			Ammonia / g manure solids				
	Lower Moisture				Med Moisture			Higher moisture				
	5% 1-1	10% 1-2	15% 1-3	1-4 Raw	5% 2-1	10% 2-2	15% 2-3	2-4 Raw	5% 3-1	10% 3-2	15% 3-3	3-4 Raw
Post Test	846.48	639.50	535.42	3625.47	138.90	87.60	98.71	3540.77	129.99	183.25	120.99	2813.39
1	34.54	24.29	44.58		27.35	25.20	38.73		41.47	56.86	30.15	
2	36.84	45.92	49.69		84.20	44.12	44.45		24.20	43.53	36.67	
3	38.55	32.02	37.69		119.05	31.89	27.40		28.12	41.55	23.32	
4	45.08	16.10	29.23		61.99	14.71	17.24		3.80	37.19	1.76	
5	48.91	19.86	32.13		81.06	12.23	45.26		22.23	24.85	11.81	
6	38.31	20.85	34.05		51.04	16.23	18.04		18.80	11.88	14.05	
7	91.98	24.35	40.83		86.47	26.83	22.35		70.47	23.73	20.85	
8	101.69	24.67	34.93		43.48	34.67	14.59		131.52	43.24	22.32	

Part II Lime Code Time(Days)	Ammonia Reduction				NH3 in ug/g			% Reduction in NH3				
	5%	10%	15%	1-4	5%	10%	15%	2-4	5%	10%	15%	3-4
	1-1	1-2	1-3	Raw	2-1	2-2	2-3	Raw	3-1	3-2	3-3	Raw
Post Test	76.65	82.36	85.23	0.00	96.08	97.53	97.21	0.00	95.38	93.49	95.70	0.00
1	99.05	99.33	98.77		99.23	99.29	98.91		98.53	97.98	98.93	
2	98.98	98.73	98.63		97.62	98.75	98.74		99.14	98.45	98.70	
3	98.94	99.12	98.96		96.64	99.10	99.23		99.00	98.52	99.17	
4	98.76	99.56	99.19		98.25	99.58	99.51		99.86	98.68	99.94	
5	98.65	99.45	99.11		97.71	99.65	98.72		99.21	99.12	99.58	
6	98.94	99.42	99.06		98.56	99.54	99.49		99.33	99.58	99.50	
7	97.46	99.33	98.87		97.56	99.24	99.37		97.50	99.16	99.26	
8	97.20	99.32	99.04		98.77	99.02	99.59		95.33	98.46	99.21	

Part II Moisture Lime Code Time(Days)	Available P in ug/g											
	Lower Moisture				Med Moisture				Higher moisture			
	5%	10%	15%	1-4	5%	10%	15%	2-4	5%	10%	15%	3-4
	1-1 P	1-2 P	1-3 P	Raw	2-1 P	2-2 P	2-3 P	Raw	3-1 P	3-2 P	3-3 P	Raw
Post Test	83.6	65	24	2604	102	36.8	30.9	2602	146	57.2	38.7	2619
1	133	60.7	31		128	46.6	27.5		46	67	57.4	
2	58.69	67.67	33.73		107.5	46.92	29.2		95.06	76.1	60.01	
3	65.38	76.1	47.84		65.42	51.61	31.97		30.05	73.9	59.55	
4	42.38	12.03	70.41		24.26	48.83	57.15		42.96	93.17	69.95	
5	116.3	52.5	81.3		121.6	231	55.8		42.1	68.6	65.4	
6	73.5	15.2	55.5		115.1	10.8	37.4		71.6	24.6	24.2	
7	67.6	18.5	40.2		133.3	23.7	34.5		141.7	49.3	27.2	
8	204	17.6	12.8		134	17.2	10.4		67.5	23.6	1.86	

Moisture Lime Code Time(Days)	Available P in ug/g per g manure solids											
	Lower Moisture				Med Moisture				Higher moisture			
	5%	10%	15%	1-4	5%	10%	15%	2-4	5%	10%	15%	3-4
	1-1 P	1-2 P	1-3 P	Raw	2-1 P	2-2 P	2-3 P	Raw	3-1 P	3-2 P	3-3 P	Raw
Post Test	253.64	140.91	44.62	8209.33	279.45	89.80	65.31	8658.90	431.31	149.74	87.36	9326.92
1	232.03	73.73	45.76		228.78	86.34	47.98		82.22	112.72	77.60	
2	67.98	98.24	51.60		165.82	85.19	42.55		119.51	108.44	87.02	
3	73.55	87.62	59.09		73.37	76.79	39.64		38.77	95.00	65.44	
4	47.17	12.48	78.86		26.57	59.85	62.77		47.04	123.70	80.51	
5	137.73	59.58	93.29		137.67	263.10	75.17		47.27	79.29	68.36	
6	82.57	16.77	61.15		128.82	12.34	42.70		79.64	27.82	26.98	
7	78.50	21.15	45.09		151.27	27.29	43.32		178.64	56.25	30.01	
8	227.96	19.56	14.11		149.00	19.05	11.32		74.73	27.43	2.02	

Part II Moisture Lime Code Time(Days)	Nitrogen (%)											
	Lower Moisture				Med Moisture				Higher moisture			
Post Test	5%	10%	15%	1-4	5%	10%	15%	2-4	5%	10%	15%	3-4
Nitrogen (%)	1-1	1-2	1-3	Raw	2-1	2-2	2-3	Raw	3-1	3-2	3-3	Raw
N	N	N	N	N	N	N	N	N	N	N	N	N
Post Test	1.12	1.18	1.14	1.06	0.97	0.77	0.88	1.02	0.73	0.92	0.81	0.99
1	1.51	1.57	1.38		1.084	0.978	1.057		0.92	1.169	1.164	
2	1.84	1.6	1.98		1.86	1.01	1.38		1.63	1.71	1.24	
3	2.37	2	1.5		1.63	1.25	1.44		1.71	1.64	1.55	
4	2.28	2.06	1.75		2.41	1.35	1.51		1.7	1.7	1.39	
5	2.35	1.95	1.72		2.42	1.52	1.33		1.89	1.9	1.46	
6	2.3	2.03	1.73		2.39	1.46	1.51		1.86	1.89	1.44	
7	2.309	1.94	1.66		2.65	1.42	1.42		1.89	1.9	1.48	
8	2.39	1.93	1.71		2.62	1.69	1.46		1.98	1.83	1.45	

Nitrogen / g solids Moisture Lime Code Time(Days)	%N in ug / g solids											
	Lower Moisture				Med Moisture				Higher moisture			
Post Test	5%	10%	15%	1-4	5%	10%	15%	2-4	5%	10%	15%	3-4
N	1-1	1-2	1-3	Raw	2-1	2-2	2-3	Raw	3-1	3-2	3-3	Raw
N	N	N	N	N	N	N	N	N	N	N	N	N
Post Test	3.40	2.56	2.12	3.34	2.66	1.88	1.86	3.39	2.16	2.41	1.83	3.53
1	2.63	1.91	2.04		1.94	1.81	1.84		1.64	1.97	1.57	
2	2.13	2.32	3.03		2.87	1.83	2.01		2.05	2.44	1.80	
3	2.67	2.30	1.85		1.83	1.86	1.79		2.21	2.11	1.70	
4	2.54	2.14	1.96		2.64	1.65	1.66		1.86	2.26	1.60	
5	2.78	2.21	1.97		2.74	1.73	1.79		2.12	2.20	1.53	
6	2.58	2.24	1.91		2.67	1.67	1.72		2.07	2.14	1.61	
7	2.68	2.22	1.86		3.01	1.64	1.78		2.38	2.17	1.63	
8	2.67	2.14	1.88		2.91	1.87	1.59		2.19	2.13	1.57	

Part II		Carbon (%)											
Moisture		Lower Moisture				Med Moisture				Higher moisture			
Lime	5%	10%	15%		5%	10%	15%		5%	10%	15%		
Code	1-1	1-2	1-3	1-4	2-1	2-2	2-3	2-4	3-1	3-2	3-3	3-4	
Time(Days)	NH3-N	NH3-N	NH3-N	Raw	NH3-N	NH3-N	NH3-N	Raw	NH3-N	NH3-N	NH3-N	Raw	
Post Test	14.21	14.86	14.75	12.02	13.08	11.45	12.26	12.6	11.19	11.84	11.18	12.16	
1	20.16	21.25	18.09		15.696	15.898	15.129		15.384	15.987	17.507		
2	25.03	22.7	26.66		22.65	17.53	21.33		26.39	23.8	18.53		
3	31.2	28.85	21.42		12.16	19.79	23.55		21.26	24.74	23.44		
4	29.92	29.23	25.95		30.8	24.24	24.17		25.47	25.47	22.72		
5	29.71	28.57	26.49		30.36	27.16	21.45		30.6	28.07	23.93		
6	29.58	29.42	24.98		31.28	26.22	24.63		30.03	26.92	24.42		
7	30.42	28.32	24.43		27.67	25.52	24.12		29.26	27.89	23.74		
8	29.99	28.79	26.81		30.36	26.96	25.02		28.27	27.21	24.9		

Carbon / g solids		%C in ug / g solids											
Moisture		Lower Moisture				Med Moisture				Higher moisture			
Lime	5%	10%	15%		5%	10%	15%		5%	10%	15%		
Code	1-1	1-2	1-3	1-4	2-1	2-2	2-3	2-4	3-1	3-2	3-3	3-4	
Time(Days)	N	N	N	Raw	N	N	N	Raw	N	N	N	Raw	
Post Test	43.11	32.21	27.42	37.89	35.84	27.94	25.91	41.93	33.06	30.99	25.24	43.30	
1	35.17	25.81	26.71		28.05	29.46	26.39		27.50	26.90	23.67		
2	28.99	32.96	40.78		34.94	31.83	31.08		33.18	33.91	26.87		
3	35.10	33.22	26.46		13.64	29.45	29.20		27.43	31.80	25.76		
4	33.30	30.33	29.06		33.73	29.71	26.55		27.89	33.82	26.15		
5	35.18	32.43	30.40		34.37	30.93	28.90		34.36	32.44	25.01		
6	33.23	32.46	27.52		35.01	29.96	28.12		33.40	30.45	27.22		
7	35.33	32.37	27.40		31.40	29.39	30.29		36.89	31.82	26.19		
8	33.51	31.99	29.55		33.76	29.87	27.24		31.30	31.62	26.98		

PHASE III TESTING WORKSHEET

Manure Raw Batch: NA

Volume Air: 60 l

Test ID: CA1

Calculated [NH₃]g: 437.5 ug/m³

Grams manure tested: 0 g

Grams Quicklime: 0 g

Test Duration: 20 min

Acid Traps	Sample ID	Volume (ml)	Concentration (mg/l)	NH ₃ Released (mg)	Time Interval (minutes)
1	CL1	250	0.07	0.0175	0-20

[NH₃] bulk : NA ug/g

[NH₃] /g solids : NA mg/g

NH₃ Total : NA mg

NH₃ Released : 291.6667 ug/m³

* Notes 1st BLANK Air Sample--- without manure or Quicklime added

PHASE III TESTING WORKSHEET

Manure Raw Batch: NA

Volume Air 60 L

Test ID: CA2

Calculated [NH₃]g: 437.5 ug/m³

Grams manure tested: 0 g

Grams Quicklime: 0 g

Test Duration: 20 min

Acid Traps	Sample ID	Volume (ml)	Concentration mg/L	NH ₃ Released mg	Time Interval (minutes)
1	CL2	250	0.07	0.0175	0-20

[NH₃] bulk : NA ug/g

[NH₃] /g solids : NA mg/g

NH₃ Total : NA mg

NH₃ Released : 291.6666667 ug/m³

* Notes 2 nd BLANK Air Sample--- without manure or Quicklime added

PHASE III TESTING WORKSHEET

T: 68 F

Humidity: 47 %

Manure Raw Batch: CR1

MC: 65.4 %

TP: 7567 ug/g %C 16.85

Test ID: CP1

MC: 64.8 %

11570 ug/g solids %N 1.49

TP: 7107 ug/g %C 16.31

Grams manure tested: 150 g

Grams Quicklime: 0 g

10968 ug/g solids %N 1.38

Test Duration: 60 min

Acid Traps	Sample ID	Volume (ml)	Concentration mg/l	avg air mg/l	NH ₃ Released mg	Corrected for atm mg	NH ₃ Released ug/g solids	Time Interval mins	Cumulative ug/g solids	RAW [NH ₃] bulk :	
1	CL3	400	0.03	0.0004	0.012	0.003	0.0578	0-10	0.0578	[NH ₃] /g solids :	2.072
2	CL4	400	0.06	0.0008	0.024	0.015	0.2890	10-20	0.3468		5.99
3	CL5	400	0.05	0.0007	0.02	0.011	0.2119	20-30	0.5588	NH ₃ Total :	310.80
4	CL6	400	0.05	0.0007	0.02	0.011	0.2119	30-40	0.7707		
5	CL7	400	0.04	0.0005	0.016	0.007	0.1349	40-50	0.9056	NH ₃ Released :	0.11
6	CL8	400	0.04	0.0005	0.016	0.007	0.1349	50-60	1.0405	NH ₃ Released/g solids :	0.00072
Deduction for atmospheric NH ₃											
Total					0.054	1.040462428	0.0000			% Released Durring test:	0.01

* Notes 1st BLANK --- without Quicklime added

Solids post-process

Bulk [NH₃] : 1992

[NH₃] /g solids : 5.66

% Released up to analysis: 5.50

PHASE III TESTING WORKSHEET

T:	68	F	Humidity:	47	%					
Manure Raw Batch:	CR1	MC:	65.4	%	TP:	7567	ug/g	%C	16.85	486.99
						11570	ug/g solids	%N	1.49	43.06
Test ID:	CP2	MC:	64.12	%	TP:	8601	ug/g	%C	16.83	469.06
						13414	ug/g solids	%N	1.42	39.58
Grams manure tested:	150	g								
Grams Quicklime:	0	g								
Test Duration:	60	min								

Acid Traps	Sample ID	Volume (ml)	Concentration mg/l	avg air mg/l	NH ₃ Released mg	Corrected for Atm mg	NH ₃ Released ug/g solids	Time Interval mins	Cumulative ug/g solids	RAW [NH ₃] bulk :	
1	CL9	400	0.03	0.0004	0.012	0.003	0.0578	0-10	0.0578	2.072	mg
2	CL10	400	0.04	0.0005	0.016	0.007	0.1349	10-20	0.1927	[NH ₃] /g solids :	5.99 mg/g
3	CL11	400	0.05	0.0007	0.02	0.011	0.2119	20-30	0.4046	NH ₃ Total :	310.8 mg
4	CL12	400	0.05	0.0007	0.02	0.011	0.2119	30-40	0.6166		
5	CL13	400	0.04	0.0005	0.016	0.007	0.1349	40-50	0.7514	NH ₃ Released :	0.10 mg
6	CL14	400	0.03	0.0004	0.012	0.003	0.0578	50-60	0.8092	NH ₃ Released/g solids :	0.00064 mg/g
					Total	0.096	0.042		0.8092	% Released Durring test:	0.01 %

* Notes 2nd BLANK --- without Quicklime added

Solids post-process
 Bulk [NH₃] : 1964.00 ug/g
 [NH₃] /g solids : 5.47 mg/g
 % Released up to analysis: 8.59 %

PHASE III TESTING WORKSHEET

		T:	70	F		Humidity:	40	%		
Manure Raw Batch:	CR2	MC:	62.7	%		TP:	7013	ug/g	%C	14.9
							11185	ug/g solids	%N	1.53
									NO ₃ -N	0.9
Test ID:	CP3	MC:	55.59	%		TP:	6825	ug/g	%C	14.33
							12277	ug/g solids	%N	1.16
Grams manure tested:	200								NO ₃ -N	2
Grams Quicklime:	20									
Test Duration:	60									

Acid Traps	Sample ID	Volume (ml)	Concentration		NH ₃ Released	Corrected for Atm	NH ₃ Released	Time Interval	Cumulative	
			mg/l	avg air mg/l	mg	mg	mg/g solids	mins	mg/g solids	
1	CL15	200	63	0.42	12.6	12.591	0.1689	0-10	0.1689	RAW [NH ₃] bulk : 2.499
2	CL16	200	0.16	0.0010667	0.032	0.023	0.0004	0-10	0.1693	[NH ₃] /g solids : 6.70
3	CL17	200	167	1.1133333	33.4	33.391	0.4477	10-20	0.6171	NH ₃ Total : 499.8
4	CL18	200	0.21	0.0014	0.042	0.033	0.0006	10-20	0.6176	
5	CL19	200	136.2	0.908	27.24	27.231	0.3651	20-30	0.9828	NH ₃ Released : 144.15
6	CL20	200	0.09	0.0006	0.018	0.009	0.0002	20-30	0.9830	NH ₃ Released/g solids : 1.93
7	CL21	200	137	0.9133333	27.4	27.391	0.3673	30-40	1.3503	
8	CL22	200	0.2	0.0013333	0.04	0.031	0.0005	30-40	1.3508	% Released Durring test: 28.84
9	CL23	200	122	0.8133333	24.4	24.391	0.3271	40-50	1.6779	
10	CL24	200	0.14	0.0009333	0.028	0.019	0.0004	40-50	1.6783	
11	CL25	200	94.7	0.6313333	18.94	18.931	0.2539	50-60	1.9322	<u>Solids post-process</u>
12	CL26	200	0.05	0.0003333	0.01	0.001	0.0001	50-60	1.9323	Bulk [NH ₃] : 56.63

* Notes 10% Quicklime 1 st Duplicate

TOTAL: 144.15 144.042 1.93230563

[NH₃] /g solids : **0.13**

% Released up to analysis: **98.10**

PHASE III TESTING WORKSHEET

		T:	70	F		Humidity:	40	%		
Manure Raw Batch:	CR2	MC:	62.7	%		TP:	7013	ug/g	%C	14.9
							11185	ug/g solids	%N	1.53
									NO ₃ -N	0.9
Test ID:	CP4	MC:	54.92	%		TP:	6407	ug/g	%C	14.74
							11666	ug/g solids	%N	1.16
Grams manure tested:	200								NO ₃ -N	0.8
Grams Quicklime:	20									
Test Duration:	60									

Acid Traps	Sample ID	Volume (ml)	Concentration		NH ₃ Released	Corrected for Atm	NH ₃ Released	Time Interval	Cumulative	
			mg/l	avg air mg/l	mg	mg	mg/g solids	mins	mg/g solids	
1	CL27	200	175	1.16666667	35	34.991	0.4692	0-10	0.4692	RAW [NH ₃] bulk : 2.499
2	CL28	200	0.39	0.0026	0.078	0.069	0.0010	0-10	0.4702	[NH ₃] /g solids : 6.70
3	CL29	200	183	1.22	36.6	36.591	0.4906	10-20	0.9608	NH ₃ Total : 499.8
4	CL30	200	0.05	0.00033333	0.01	0.001	0.0001	10-20	0.9610	
5	CL31	200	189	1.26	37.8	37.791	0.5067	20-30	1.4677	NH ₃ Released : 195.15
6	CL32	200	0.76	0.00506667	0.152	0.143	0.0020	20-30	1.4697	NH ₃ Released/g solids : 2.62
7	CL33	200	189	1.26	37.8	37.791	0.5067	30-40	1.9764	
8	CL34	200	0.46	0.00306667	0.092	0.083	0.0012	30-40	1.9776	% Released Durring test: 39.05
9	CL35	200	134	0.89333333	26.8	26.791	0.3592	40-50	2.3369	
10	CL36	200	0.85	0.00566667	0.17	0.161	0.0023	40-50	2.3392	
11	CL37	200	103	0.68666667	20.6	20.591	0.2761	50-60	2.6153	<u>Solids post-process</u>
12	CL38	200	0.24	0.0016	0.048	0.039	0.0006	50-60	2.6160	Bulk [NH ₃] : 40.03

* Notes 10% Quicklime 2 nd Duplicate
Modified mixing blade

TOTAL: 195.15 195.042 2.615951743

[NH₃] /g solids : **0.09**

% Released up to analysis: **98.67**

PHASE III TESTING WORKSHEET

		T:	66	F	Humidity:	47	%				
Manure Raw Batch:	CR3	MC:	63.62	%	TP:	15708	ug/g	%C	15.87	436.23	mg/g solids
						24690	ug/g solids	%N	1.46	40.13	
								NO ₃ -N	0.7	1.92	ug/g solids
Test ID:	CP5	MC:	50.64	%	TP:	4825	ug/g	%C	13.65	276.54	
						9528	ug/g solids	%N	1	20.26	
Grams manure tested:	200							NO ₃ -N	0.7	1.42	ug/g solids
Grams Quicklime:	30										
Test Duration:	60										

		Volume (ml)	Concentration	Corrected		NH ₃ Released	Time Interval	Cumulative			
Acid Traps	Sample ID	mg/l	avg air mg/l	mg	for atm	mg/g solids	mins	mg/g solids			
1	CL39	200	139	0.9253	27.76	27.751	0-10	0.3815	RAW [NH ₃] bulk :	2.491	mg/g
2	CL40	200	0.4	0.0027	0.08	0.071	0-10	0.3826	[NH ₃] /g solids :	6.85	mg/g
3	CL41	200	170	1.1320	33.96	33.951	10-20	0.8494	NH ₃ Total :	498.2	mg
4	CL42	200	0.64	0.0043	0.128	0.119	10-20	0.8511			
5	CL43	200	139	0.9293	27.88	27.871	20-30	1.2343	NH ₃ Released :	150.35	mg
6	CL44	200	0.06	0.0004	0.0126	0.0036	20-30	1.2345	NH ₃ Released/g solids :	2.07	mg/g
7	CL45	200	73.8	0.4920	14.76	14.751	30-40	1.4373			
8	CL46	200	0.43	0.0029	0.086	0.077	30-40	1.4385	% Released Durring test:	30.18	%
9	CL47	200	113	0.7533	22.6	22.591	40-50	1.7491			
10	CL48	200	0.11	0.0007	0.022	0.013	40-50	1.7494			
11	CL49	200	115	0.7680	23.04	23.031	50-60	2.0661	<u>Solids post-process</u>		
12	CL50	200	0.09	0.0006	0.0172	0.0082	50-60	2.0663	Bulk [NH ₃] :	42.00	ug/g
* Notes	15% Quicklime 1 st Duplicate				TOTAL:	150.3458	150.2378	2.066324904	[NH ₃] /g solids :	0.09	mg/g
									% Released up to analysis:	98.76	%

PHASE III TESTING WORKSHEET

		T:	66	F	Humidity:	47	%				
Manure Raw Batch:	CR3	MC:	63.62	%	TP:	15708	ug/g	%C	15.87	mg/g solids	436.2287
						24690	ug/g solids	%N	1.46		40.131941
								NO ₃ -N	0.7		1.9241341 ug/g solids
Test ID:	CP6	MC:	52.1	%	TP:	11670	ug/g	%C	14.51		302.92276
						22399	ug/g solids	%N	1.09		22.755741
Grams manure tested:	200							NO ₃ -N	0.7		1.4613779 ug/g solids
Grams Quicklime:	30										
Test Durration:	60	min									
		Volume (ml)	Concentration		NH ₃ Released	Corrected	NH ₃ Released	Time Interval	Cumulative		
Acid Traps	Sample ID		mg/l	avg air mg/l	mg	for Atm	mg/g soilds	mins	mg/g soilds	[NH ₃] bulk :	2.491 mg/g
1	CL51	200	166	1.1053	33.16	33.151	0.4557	0-10	0.4557	[NH ₃] /g solids :	6.85 mg/g
2	CL52	200	0.26	0.0017	0.052	0.043	0.0007	0-10	0.4565		
3	CL53	200	208	1.3867	41.6	41.591	0.5717	10-20	1.0282	NH ₃ Total :	498.2 mg
4	CL54	200	0.42	0.0028	0.084	0.075	0.0012	10-20	1.0294		
5	CL55	200	93	0.6200	18.6	18.591	0.2556	20-30	1.2850	NH ₃ Released :	154.09 mg
6	CL56	200	0.05	0.0003	0.01	0.001	0.0001	20-30	1.2851	NH ₃ Released/g solids :	2.12 mg/g
7	CL57	200	84.8	0.5653	16.96	16.951	0.2331	30-40	1.5182		
8	CL58	200	0.02	0.0001	0.004	-0.005	0.0001	30-40	1.5183	% Released Durring test:	30.93 %
9	CL59	200	74.1	0.4937	14.812	14.803	0.2036	40-50	1.7219		
10	CL60	200	0.02	0.0001	0.004	-0.005	0.0001	40-50	1.7219		
11	CL61	200	144	0.9600	28.8	28.791	0.3958	50-60	2.1177	<u>Solids post-process</u>	
12	CL62	200	0.02	0.0001	0.0034	-0.0056	0.0000	50-60	2.1178	Bulk [NH ₃] :	42.30 ug/g
* Notes	15% Quicklime 2 nd Duplicate				TOTAL:	154.0894	153.9814	2.117776251		[NH ₃] /g solids :	0.09 mg/g
										% Released up to analysis:	98.71 %

PHASE III TESTING WORKSHEET

		T:	65	F	Humidity:	42	%			
Manure Raw Batch:	CR4	MC:	61.53	%	TP:	ug/g	%C	15.87	412.53	
							%N	1.43	37.17	
	Test ID:	CP2	MC:	48.04	%	TP:	ug/g	%C	12.7	244.42
							%N	1.04	20.02	
Grams manure tested:	200	g								
Grams Quicklime:	20	g								
Test Durration:	60	min								

Acid Traps	Sample ID	Volume (ml)	concentration	NH ₃ Released	Corrected for Atm	NH ₃ Released	Time Interval	Cumulative	
		mg/l	avg air mg/l	mg	mg	mg/g soilds	mins	mg/g soilds	
1	CL63	200	121	0.806666667	24.2	24.191	0-10	0.3145	[NH ₃] bulk : 3.196
2	CL64	200	0.06	0.0004	0.012	0.003	0-10	0.3147	[NH ₃] /g solids : 8.31
3	CL65	200	180	1.2	36	35.991	10-20	0.7826	NH ₃ Total : 639.2
4	CL66	200	0.28	0.001866667	0.056	0.047	10-20	0.7833	
5	CL67	200	144	0.96	28.8	28.791	20-30	1.1576	NH ₃ Released : 161.25
6	CL68	200	0.03	0.0002	0.006	-0.003	20-30	1.1577	NH ₃ Released/g solids : 2.10
7	CL69	200	169	1.126666667	33.8	33.791	30-40	1.5970	
8	CL70	200	0.12	0.0008	0.024	0.015	30-40	1.5973	% Released Durring test: 25.23
9	CL71	200	72.2	0.481333333	14.44	14.431	40-50	1.7850	
10	CL72	200	0.48	0.0032	0.096	0.087	40-50	1.7862	
11	CL73	200	119	0.793333333	23.8	23.791	50-60	2.0956	<u>Solids post-process</u>
12	CL74	200	0.1	0.000666667	0.02	0.011	50-60	2.0958	Bulk [NH ₃] : 82.30

* Notes 10% quicklime dosage trial

TOTAL: 161.254 161.146 2.095840915

[NH₃] /g solids : 0.16

% Released up to analysis: 98.09

PHASE III TESTING WORKSHEET

T: 65 F Humidity: 42 %

Manure Raw Batch: CR4

MC: 61.53 %

TP: ug/g

%C 15.87 mg/g solids 412.53
%N 1.43 37.17

Test ID: CP7

MC: 48.04 %

TP: ug/g

%C 12.7 mg/g solids 244.42
%N 1.04 20.02

Grams manure tested: 200 g

Grams Quicklime: 20 g

Test Duration: 60 min

Acid Traps	Sample ID	Volume (ml)	concentration mg/l	avg air mg/l	NH ₃ Released mg	Corrected for Atm mg	NH ₃ Released mg/g solids	Time Interval mins	Cumulative mg/g solids	
										[NH ₃] bulk : 3.196
1	CL63	200	121	0.806666667	24.2	24.191	0.3145	0-10	0.3145	[NH ₃]/g solids : 8.31
2	CL64	200	0.06	0.0004	0.012	0.003	0.0002	0-10	0.3147	
3	CL65	200	180	1.2	36	35.991	0.4679	10-20	0.7826	NH ₃ Total : 639.2
4	CL66	200	0.28	0.001866667	0.056	0.047	0.0007	10-20	0.7833	
5	CL67	200	144	0.96	28.8	28.791	0.3743	20-30	1.1576	NH ₃ Released : 161.25
6	CL68	200	0.03	0.0002	0.006	-0.003	0.0001	20-30	1.1577	NH ₃ Released/g solids : 2.10
7	CL69	200	169	1.126666667	33.8	33.791	0.4393	30-40	1.5970	
8	CL70	200	0.12	0.0008	0.024	0.015	0.0003	30-40	1.5973	% Released Durring test: 25.23
9	CL71	200	72.2	0.481333333	14.44	14.431	0.1877	40-50	1.7850	
10	CL72	200	0.48	0.0032	0.096	0.087	0.0012	40-50	1.7862	
11	CL73	200	119	0.793333333	23.8	23.791	0.3093	50-60	2.0956	<u>Solids post-process</u>
12	CL74	200	0.1	0.000666667	0.02	0.011	0.0003	50-60	2.0958	Bulk [NH ₃] : 82.30

* Notes 10% quicklime dosage trial

TOTAL: 161.254 161.146 2.095840915

[NH₃]/g solids : 0.16

% Released up to analysis: 98.09

PHASE III TESTING WORKSHEET

T: 65 F Humidity: 42 %

Manure Raw Batch: CR4

MC: 61.53 %

TP: NA ug/g

%C 15.87 mg/g solids
%N 1.43 412.52924
37.171822

Test ID: CP2

MC: 44.53 %

TP: NA ug/g

%C 12.73 mg/g solids
%N 1 229.49342
18.027763

Grams manure tested: 200 g

Grams Quicklime: 30 g

Test Duration: 60 min

Acid Traps	Sample ID	Volume (ml)	Concentration mg/l	avg air mg/l	NH ₃ Released mg	corrected for Ati mg	NH ₃ Released mg/g solids	Time Interval mins	Cumulative mg/g solids		
1	CL75	200	84.78	0.5652	16.956	16.947	0.2204	0-10	0.2204	[NH ₃] bulk :	3.196 mg/g
2	CL76	200	0.06	0.0004133	0.0124	0.0034	0.0002	0-10	0.2205	[NH ₃] /g solids :	8.31 mg/g
3	CL77	200	264	1.76	52.8	52.791	0.6862	10-20	0.9068	NH ₃ Total :	639.2 mg
4	CL78	200	0.07	0.00044	0.0132	0.0042	0.0002	10-20	0.9070		
5	CL79	200	125	0.8333333	25	24.991	0.3249	20-30	1.2319	NH ₃ Released :	182.94 mg
6	CL80	200	0.06	0.0004133	0.0124	0.0034	0.0002	20-30	1.2321	NH ₃ Released/g solids :	2.38 mg/g
7	CL81	200	178	1.1866667	35.6	35.591	0.4627	30-40	1.6947		
8	CL82	200	0.15	0.001	0.03	0.021	0.0004	30-40	1.6951	% Released Durring test:	28.62 %
9	CL83	200	178	1.1866667	35.6	35.591	0.4627	40-50	2.1578		
10	CL84	200	0.04	0.00024	0.0072	-0.0018	0.0001	40-50	2.1579		
11	CL85	200	84.44	0.5629333	16.888	16.879	0.2195	50-60	2.3774	<u>Solids post-process</u>	
12	CL86	200	0.104	0.0006933	0.0208	0.0118	0.0003	50-60	2.3777	Bulk [NH ₃] :	70.60 ug/g

* Notes 15% quicklime dosage trial

TOTAL: 182.94 182.832 2.377696907

[NH₃] /g solids : 0.13 mg/g

% Released up to analysis: 98.47 %

Part IV

Long Term Volatilization

Duplicate #1

[NH3] bulk : 3.55 mg/g primary analysis as a solid
 [NH3] bulk : 4.55 mg/g Sec as a liquid (no waste)
 [NH3] /g manure : 9.971910112 mg/g primary analysis as a solid
 [NH3] /g manure : 12.78089888 mg/g Sec as a liquid (no waste)
 MC: 64.4 %

Concentration	NH3 Released	Cumulative	Cumulative	Time Interval	Time Interval	Volitization Rate	Volitization Rate	
mg/l	avg air mg/l	mg	mg/g manure	ug/g dry solids	days	mg/hour	ug/g dry solids/min	
458	1.017777778	91.6	0.458	1287	0-30mins	0.02	183.20	42.88
288	0.64	57.6	0.746	2096	30-60mins	0.04	115.20	26.97
206	0.457777778	41.2	0.952	2674	60-90mins	0.06	82.40	19.29
87	0.193333333	17.4	1.039	2919	90-120mins	0.08	34.80	8.15
121	0.134444444	24.2	1.16	3258	2-3hours	0.13	24.20	5.66
83	0.092222222	16.6	1.243	3492	3-4hours	0.17	16.60	3.89
93	0.103333333	18.6	1.336	3753	4-5hours	0.21	18.60	4.35
68	0.075555556	13.6	1.404	3944	5-6hours	0.25	13.60	3.18
281	0.052037037	56.2	1.685	4733	6-12 hours	0.50	9.37	2.19
100	0.018518519	20	1.785	5014	12-18hours	0.75	3.33	0.78
219	0.040555556	43.8	2.004	5629	18-24hours	1.00	7.30	1.71
177	0.016388889	35.4	2.181	6126	24-36hours	1.50	2.95	0.69
332	0.030740741	66.4	2.513	7059	36-48hours	2.00	5.53	1.30
212	0.01962963	42.4	2.725	7654	48-60hours	2.50	3.53	0.83
91.5	0.008472222	18.3	2.8165	7912	60-72hours	3.00	1.53	0.36
310	0.014351852	62	3.1265	8782	3-4days	4.00	2.58	0.60
238	0.011018519	47.6	3.3645	9451	4-5days	5.00	1.98	0.46
199	0.009212963	39.8	3.5635	10010	5-6days	6	1.66	0.39
121	0.005601852	24.2	3.6845	10350	6-7days	7	1.01	0.24
80	0.003703704	16	3.7645	10574	7-8days	8	0.67	0.16
51	0.002361111	10.2	3.8155	10718	8-9days	9	0.43	0.10
38	0.001759259	7.6	3.8535	10824	9-10days	10	0.32	0.07
31	0.001435185	6.2	3.8845	10912	10-11days	11	0.26	0.06
66	0.001527778	13.2	3.9505	11097	11-13days	13	0.28	0.06
74	0.001712963	14.8	4.0245	11305	13-15days	15	0.31	0.07
67	0.001550926	13.4	4.0915	11493	15-17days	17	0.28	0.07
54	0.00125	10.8	4.1455	11645	17-19days	19	0.23	0.05
	0	0	4.1455	11645	19-21days	21	0.00	0.00
	0	0	4.1455	11645	21-23days	23	0.00	0.00
	0	0	4.1455	11645	23-25days	25	0.00	0.00
	0	0	4.1455	11645	25-28days	28	0.00	0.00
	TOTAL:	829.1						

Part IV Long Term Volatilization		Duplicate #2		[NH3] bulk :	3.55	mg/g	primary analysis as a solid	
				[NH3] bulk :	4.55		Sec as a liquid (no waste)	
MC:		64.4	%	IH3] /g manure	9.971910112	mg/g		
Grams manure test		200	g	IH3] /g manure	12.78089888			
Concentration		NH3 Released	Cumulative	Cumulative	Time Interval	Time Interval	Volitization Rate	
mg/l	avg air mg/l	mg	mg/g manure	mg/g dry solids		days	mg/hour	mg/g dry solids/min
613	1.362222222	122.6	0.613	1722	0-30mins	0.02	245.20	57.40
461	1.024444444	92.2	1.074	3017	30-60mins	0.04	184.40	43.16
154	0.342222222	30.8	1.228	3449	60-90mins	0.06	61.60	14.42
75	0.166666667	15	1.303	3660	90-120mins	0.08	30.00	7.02
89	0.098888889	17.8	1.392	3910	2-3hours	0.13	17.80	4.17
69	0.076666667	13.8	1.461	4104	3-4hours	0.17	13.80	3.23
52	0.057777778	10.4	1.513	4250	4-5hours	0.21	10.40	2.43
47	0.052222222	9.4	1.56	4382	5-6hours	0.25	9.40	2.20
215	0.039814815	43	1.775	4986	6-12 hours	0.50	7.17	1.68
61.3	0.011351852	12.26	1.8363	5158	720-1440	0.75	2.04	0.48
217	0.040185185	43.4	2.0533	5768	1440-2160	1.00	7.23	1.69
96.2	0.008907407	19.24	2.1495	6038	2160-2880	1.50	1.60	0.38
307	0.028425926	61.4	2.4565	6900	2880-3600	2.00	5.12	1.20
74.7	0.006916667	14.94	2.5312	7110	3600-4320	2.50	1.25	0.29
222	0.020555556	44.4	2.7532	7734	5760	3.00	3.70	0.87
143	0.00662037	28.6	2.8962	8135	7200	4.00	1.19	0.28
246	0.011388889	49.2	3.1422	8826	8640	5.00	2.05	0.48
164	0.007592593	32.8	3.3062	9287	5-6days	6	1.37	0.32
117	0.005416667	23.4	3.4232	9616	6-7days	7	0.98	0.23
105	0.004861111	21	3.5282	9911	7-8days	8	0.88	0.20
91	0.004212963	18.2	3.6192	10166	8-9days	9	0.76	0.18
20	0.000925926	4	3.6392	10222	9-10days	10	0.17	0.04
29	0.001342593	5.8	3.6682	10304	10-11days	11	0.24	0.06
63	0.001458333	12.6	3.7312	10481	11-13days	13	0.26	0.06
77	0.001782407	15.4	3.8082	10697	13-15days	15	0.32	0.08
79	0.001828704	15.8	3.8872	10919	15-17days	17	0.33	0.08
52	0.001203704	10.4	3.9392	11065	17-19days	19	0.22	0.05
	0	0	3.9392	11065	19-21days	21	0.00	0.00
	0	0	3.9392	11065	21-23days	23	0.00	0.00
	0	0	3.9392	11065	23-25days	25	0.00	0.00
	0	0	3.9392	11065	25-27days	28	0.00	0.00
	TOTAL:	787.84						

PHASE 5

RUN #	Environmental Conditions			Temperatures			NH3 balance						
	Run 16	Run 17	Run 18	Run 16	Run 17	Run 18	Run 16	Run 17	Run 18				
16-18	9.7 OC			T1	17	17.9	18.3 °C	in	1402.80	1402.80	1402.80 mg/min		
	Pressure							out	1403.26	1349.31	1287.01 mg/min		
	Humidity 0.71			T2	18.1	18.9	19.4 °C	captured	24.88	29.53	37.29 mg/min		
Date	12/5/2003			T3	19	20.1	21 °C	unaccounte	-25.34	23.96	78.50 mg/min		
Elapsed Tir	10:50-1:30							Reduction	1.77	2.11	2.66		
Auger Spee	Run 16	Run 17	Run 18	Manure	9.7	9.8	9.8 °C						
	9.6	16.6	21.6	pH	6.8								
Residence	0	22.5	45 degree incline	Product	21	22.4	24.1 °C						
	3:50			pH	11.2	11.7	12.2						
				Air	9.7	9.8	9.9 °C						
Flow Rates	Ammonia per minute												
Manure	525 g/min			Run 16	Run 17	Run 18	Run 16	Run 17	Run 18	Run 16	Run 17	Run 18	
Quicklime	53 g/min			Acid Trap #	17.2	19.97	21 mg/l	8.6	9.985	10.5 mg NH3	0.0955556	0.110944444	0.35 mg/l air
				Acid Trap #	17.14	20.21	25.29 mg/l	8.57	10.105	12.645 mg NH3	0.0952222	0.112277778	0.4215 mg/l air
				Acid Trap #	15.42	18.88	28.29 mg/l	7.71	9.44	14.145 mg NH3	0.0856667	0.104888889	0.4715 mg/l air
	Run 16	Run 17	Run 18		49.76	59.06	74.58						
Trap Gas	9	9	3 ft3/min	mg/l									
Angle	0	22.5	45	Raw	2672	2672	2672	18.4	1.64	63.83 as is			
				Product	2427.7778	2334.4444	2226.6667	15.97	1.26	53.09	53.1	52.8	
				Raw	7387.3376	7387.3376	7387.3376	0	50.870887	4.5341443	63.83 adjusted for MC		
				Product	5175.395	4976.4324	4746.678	0	34.043914	2.6859945	53.09		
				Raw	7387.3376	7387.3376	7387.3376	46651.921	50.870887	4.1219494	63.83 Adjusted for ql dilution		
				Product	5692.9345	5474.0757	5221.3458	0	37.448305	2.9545939	53.09		
NOTES				NH3	NH3	NH3	TKN	%C	%N	mc			

This set of experiments were to gauge the effect of increased mixing intensity while leaving the residence time unchanged. Originally level and consequently raised to angles of 22.5 and 45 degrees incline while increasing auger speed to compensate for gravity to keep the same residence time. The secondary trap was determined unnecessary and consequently removed from the system. density = 1.0
 Observation 1: At 10% quicklime the steeper angles resulted in a more thoroughly mixed product which had a harder and more spherical shape.
 Observation 2: Again the process of weighing out the samples of the product for acidification takes 2-4 mins
 With such increased exposure/area ammonia must be lost in a significant proportion.

PHASE 5		Environmental Conditions		Temperatures		NH3 balance	
RUN #	19	Temperature	10.2 °C	T1	18.7 °C	in	1497.30 mg/min
		Pressure		T2	21.5 °C	out	1408.88 mg/min
Date	12/12/2003	Humidity	0.53	T3	23.8 °C	captured	35.67 mg/min
Elapsed Time	10:10-1:40					unaccount	52.76 mg/min
Auger Speed	16.5			Manure	9.9 °C	Reduction	2.38 %
Residence Time	5:14			pH	7		
				Product	29.8 °C		
				pH	12.4		
				Air	10.2 °C		
Flow Rates		Ammonia per minute					Run 16
Manure	525 g/min	Acid Trap	16.54	mg/l	8.27	mg NH3	0.0918889 mg/l air
Quicklime	53 g/min	Acid Trap	23.88	mg/l	11.94	mg NH3	0.1326667 mg/l air
		Acid Trap	30.91	mg/l	15.455	mg NH3	0.1717222 mg/l air
Trap Gas	Run 19 9 ft3/min		71.33				
		Raw	2852	mg/l	18.4	1.64	63.83 as is
		Product	2437.5		15.97	1.26	51.56
				per kilogram			
		Raw	7884.988		50.87089	4.534144	63.83 adjusted for MC
		Product	5031.998		32.96862	2.601156	51.56
				per kilogram solids			
		Raw	7884.988		50.87089	4.121949	63.83 Adjusted for ql dillution
		Product	5535.198		36.26548	2.861272	51.56
				per kilogram manure			
NOTES		NH3		%C	%N	mc	

This experimental run was to determine if ammonia capture can be enhanced by using a jog type operation of the auger by running the screw intermittently. The auger was ran at 1 minute intervals which increased residence time.
 2nd Raw density = 1.0
 Observation 1: The increased temperature was expected with the increased residence time.

PHASE 5

Environmental Conditions		Temperatures										
RUN #	20-22	Temperature	11.4 °C	Run 20	Run 21	Run 22						
Run #20- @ 10% QL				T1	19.8	19.9	20.1 °C					
Run #21 @ 15% QL		Pressure		T2	22	23	25.2 °C					
Run #22 @ 20% QL				T3	24.1	25.1	29.2 °C					
Date	12/12/2003	Humidity	0.5	Manure	9.8	9.8	9.9 °C					
Elapsed Time	1:40-5:30			Product	11.9	12.4	12.4					
Auger Speed	16.5			Air	36.6	47.8	58.1 °C					
Residence Time	4:10				7.1							
					11.4	11.4	11.4 °C					
Flow Rates				NH3 balance								
Manure	427 g/min			Run 20	Run 21	Run 22						
Quicklime	43 g/min			in	1291.68	1291.68	1291.68 mg/min					
	65			out	1259.08	1267.12	1246.84 mg/min					
Trap Gas	9 ft3/min			captured	27.05	41.67	49.62 mg/min					
Residence time	0.145833333			unaccounted	5.55	-17.11	-4.78 mg/min					
				Reduction	2.09	3.23	3.84					
Ammonia per minute												
Acid Trap #1	Run 20	Run 21	Run 22	Run 20	Run 21	Run 22	Run 20	Run 21	Run 22	Run 20	Run 21	Run 22
	7.55	8.2	8.71	3.775	4.1	4.355	0.04	0.05	0.05	0.04	0.05	0.05
Acid Trap #2	13.84	29.15	34.24	6.92	14.575	17.12	0.08	0.16	0.19	0.08	0.16	0.19
Acid Trap #3	32.71	45.98	56.28	16.355	22.99	28.14	0.18	0.26	0.31	0.18	0.26	0.31
	Run 20	Run 21	Run 22	Run 20	Run 21	Run 22	Run 20	Run 21	Run 22			
	mg/l	per kilogram			Run 20	Run 21	Run 22	Run 20	Run 21	Run 22		
Raw	3025	3025	3025	15900	15900	15900	76.53	76.53	76.53	as is		
Product	2679	2696	2653	15000	13800	12000	60.5	54.66	47.72			
		per kilogram solids			Run 20	Run 21	Run 22	Run 20	Run 21	Run 22		
Raw	12889	12889	12889	67746	67746	67746	76.53	76.53	76.53	adjusted for MC		
Product	6782	5946	5074	37975	30437	22953	60.5	54.66	47.72			
		per kilogram manure			Run 20	Run 21	Run 22	Run 20	Run 21	Run 22		
Raw	12889	12889	12889	67746	67746	67746	76.53	76.53	76.53	Adjusted for ql dilution		
Product	7460	6838	6089	41772	35002	27544	60.5	54.66	47.72			
	NH3	NH3	NH3	TKN	TKN	TKN	mc	mc	mc			

NOTES

Doses of 10, 15, and 20% quicklime were used to determine the dosage effect.

Higher moisture manure was collected by running the belt continuously over a 2 day period

density = 1.0

Observation 1: The higher moisture manure does not clump well at these doses.

Observation 2: From appearance of the interior of the product a greater amount of quicklime is dissolved or hydrated at this higher moisture content.

PHASE 5

RUN #	23-25	Environmental Conditions		Temperatures									
		Temperatur	9.9 °C	Run 23	Run 24	Run 25							
		Pressure		T1	19.8	17.5	15.3 °C						
Date	12/15/2003	Humidity	0.73	T2	21.2	18.1	17.1 °C						
Elapsed Time	10:15-2:50			T3	23.4	19.6	18.4 °C						
Auger Speed	17.5			Manure	9.9	10	10.1 °C						
Residence Time	5:10			pH	11.8	11.7	12.1						
				Product	34.1	29.8	28.4 °C						
				pH	7.2								
				Air	9.9	10	10.1 °C						
Flow Rates				NH3 balance									
Manure	285 g/min			Run 23	Run 24	Run 25							
Quicklime	28.9 g/min			in	862.125	862.125	862.125 mg/min						
				out	780.04	796.41	787.44 mg/min						
				captured	16.67	29.37	32.28 mg/min						
				unaccounted	65.41	36.35	42.40 mg/min						
				Reduction	1.93	3.41	3.74						
Trap Gas	Run 23	Run 24	Run 25										
	9	12	15 ft3/min										
	Ammonia per minute												
		Run 23	Run 24	Run 25	Run 23	Run 24	Run 25						
	Acid Trap #1	3.74	3.75	3.32	mg/l	1.87	1.875	1.66	mg NH3	0.0207778	0.015625	0.0110667	mg/l air
	Acid Trap #2	9.69	22.41	25.01	mg/l	4.845	11.205	12.505	mg NH3	0.0538333	0.093375	0.0833667	mg/l air
	Acid Trap #3	19.91	32.58	36.23	mg/l	9.955	16.29	18.115	mg NH3	0.1106111	0.13575	0.1207667	mg/l air
		Run 23	Run 24	Run 25	Run 23	Run 24	Run 25	as is					
	Raw	3025	3025	3025	mg/l	76.53	76.53	76.53	per kilogram				
	Product	2485	2537.1429	2508.5714	mg/l	58.99	53.99	50.86	per kilogram solids				
	Raw	12888.794	12888.794	12888.794	mc	76.53	76.53	76.53	adjusted for MC				
	Product	6059.4977	5514.3292	5104.948	mc	58.99	53.99	50.86	Adjusted for ql dilution				
	Raw	12888.794	12888.794	12888.794	mc	76.53	76.53	76.53	per kilogram manure				
	Product	6665.4475	6065.7621	5615.4428	mc	58.99	53.99	50.86					
		NH3	NH3	NH3	mc	mc	mc						

NOTES

Higher moisture manure (76%) was used in this series of experiments to further examine the role of increasing air flow as it relates to ammonia volatilization.

Higher moisture manure was collected by running the belt continuously over a 2 day period

3rd Raw

density = 1.0

Observation 1: Higher air flow rates resulted in lower stabilization temperatures.

Observation 2: The higher moisture manure has a more consistant flow from the manuralator nozzle.

7-May PHASE 5

RUN #	29
Run #14 @ 10% QL	
Run #15 @ 15% QL	
Date	12/15/2003
Elapsed Time	2:30-4:30
Auger Speed	12
Residence Time	3:20
Flow Rates	
Manure	285 g/min
Quicklime	42.1 g/min
Trap Gas	9 ft ³ /min

Environmental Conditions	
Temperature	12.4 °C
Pressure	
Humidity	40%

Temperatures	
T1	19.4 °C
T2	22.6 °C
T3	24.1 °C
Manure	11.8 °C
pH	12.1
Product	51.4 °C
pH	6.9
Air	12.4 °C

NH3 balance	
in	761.52 mg/min
out	674.19 mg/min
captured	14.23 mg/min
unaccounted	73.11 mg/min
Reduction	1.87 %

Ammonia			
Acid Trap #1	7.74 mg/l	3.87 mg NH3	0.04 mg/l air
Acid Trap #2	9.5 mg/l	4.75 mg NH3	0.05 mg/l air
Acid Trap #3	11.21 mg/l	5.605 mg NH3	0.06 mg/l air
mg/l per kilogram			
Raw	2672	76.53 as is	
Product	2061.111	46.78	
per kilogram solids			
Raw	11384.75	76.53 adjusted for MC	
Product	3872.813	46.78	
per kilogram manure			
Raw	11384.75	76.53 Adjusted for ql dillution	
Product	4260.094	46.78	
NH3 mc mc			

NOTES

This was performed with 15% quicklime with the higher moisture manure to have data for reproducibility and gauge dosage effects. Differences between this run and those at 15% quicklime at the medium moisture content and a those at 15% with lower moisture manure.

DUPLICATE

Observation 1: Large difference in temperature than previous runs with lower doses of quicklime.

PHASE 5

PHASE 5		Environmental Conditions		Temperatures		NH3 balance				
RUN #	27-28	Temperature	10.1 °C	Run 27	Run 28		Run 27	Run 28		
		Pressure		T1	25.1	29.8 °C	in	996.91	996.91 mg/min	
Date	12/8/2003	Humidity	29%	T2	26.9	31.3 °C	out	897.42	966.05 mg/min	
Elapsed Time	10:40-2:20			T3	28.6	33.6 °C	captured	28.65	31.15 mg/min	
Auger Speed	16.6			Manure	16.1	26 °C	unaccounted	70.84	-0.29 mg/min	
Residence Time	3:02			pH	12.1	12.2	Reduction	2.87	3.12 %	
				Product	50.4	60.6 °C				
				pH	6.9					
				Air	14.1	18.2 °C				
<u>Flow Rates</u>										
Manure	301 g/min			Ammonia						
Quicklime	30 g/min			Run 27	Run 28	Run 27	Run 28	Run 27	Run 28	
Trap Gas	9 ft ³ /min			Acid Trap #1	5	6.1 mg/l	2.5	3.05 mg NH3	0.03	0.033889 mg/l air
				Acid Trap #2	18.2	19.7 mg/l	9.1	9.85 mg NH3	0.101111	0.109444 mg/l air
				Acid Trap #3	34.1	36.5 mg/l	17.05	18.25 mg NH3	0.189444	0.202778 mg/l air
					Run 27	Run 28			Run 27	Run 28
					mg/l per kilogram					
				Raw	3312	3312	63.83	63.83	as is	
				Product	2711.25	2918.571	52.22	51.61		
					per kilogram solids					
				Raw	9157	6932	63.83	63.83	adjusted for MC	
				Product	5674	6031	52.22	51.61		
					per kilogram manure					
				Raw	9157	6932	63.83	63.83	Adjusted for ql dillution	
				Product	6242	6634	52.22	51.61		
					NH3	NH3	mc	mc		

NOTES

Temperature was manipulated by using a propane heater to heat building/manure prior to stabilization.

10% quicklime doses were used in all runs.

density = 1.0

Observation 1: It takes a long time to heat manure/manuralator 10 degrees celcius.

Observation 2: Manure consistency declined as temperature increases requiring re-calibration of manuralator several times before stable enough to take data.

PHASE 5

Environmental Conditions		Temperatures										
RUN #	29-31	Temperatu	9.4 °C	Run 29	Run 30	Run 31						
Run #29 @ 10% QL				T1	11.1	12.1	12.4 °C					
Run #30 @ 15% QL		Pressure		T2	14.1	14.7	17.1 °C					
Run #31 @ 20% QL				T3	15.6	16.3	19.2 °C					
Date	12/21/2003	Humidity	0.41									
Elapsed Time	12:50:00 PM - 5:30 PM			Manure	9.8	9.9	9.9 °C					
Auger Speed	16.6			pH	9.9	10.1	10.4					
Residence Time	2:25			Product	20.1	21.2	24.7 °C					
				pH	6.6							
				Air	9.4	9.5	9.5 °C					
								NH3 balance				
Flow Rates					Run 29	Run 30	Run 31					
Manure	302	g/min		in	1000.22	1000.22	1000.22	mg/min				
Quicklime	30	44.7	60.2	g/min	out	969.77	954.83	908.35 mg/min				
	45	60			captured	1.88	2.72	3.80 mg/min				
Trap Gas	Run 29	Run 30	Run 31		unaccounted	28.57	42.67	88.08 mg/min				
Ammonia per minute	9	9	9	ft3/min	Reduction	0.19	0.27	0.38 %				
								accounting for dilution to sample bottle				
Acid Trap #1	Run 29	Run 30	Run 31	mg/l	Run 29	Run 30	Run 31	mg NH3	Run 29	Run 30	Run 31	mg/l air
Acid Trap #2	0.83	1.35	1.61	0.415	0.675	0.805	0.005	0.008	0.008	0.010	0.013	0.009
Acid Trap #3	1.42	1.81	2.41	0.71	0.905	1.205	0.008	0.008	0.013	0.020		0.013
	1.51	2.28	3.57	0.755	1.14	1.785	0.008	0.008	0.013	0.020		0.020
Raw	Run 29	Run 30	Run 31	mg/l	Run 29	Run 30	Run 31	as is				
Product	3312	3312	3312	51.61	51.61	51.61						
	2921	2876	2736	49.53	47.51	46.78						
Raw	per kilogram solids			51.61	51.61	51.61		adjusted for MC				
Product	6844.38934	6844.389	6844.389	49.53	47.51	46.78						
	5787.59659	5479.139	5140.924									
Raw	per kilogram manure			51.61	51.61	51.61		Adjusted for ql dilution				
Product	6844.38934	6844.389	6844.389	49.53	47.51	46.78						
	6366.35625	6301.01	6169.109									
	NH3	NH3	NH3	mc	mc	mc						

This set of experiments was to examine the moisture content effect by using manure at the dryest state which would flow from the manuralator. Dry manure was tested against doses of 10, 15, and 20% quicklime.

density = 1.0

Observation 1: Almost no smell of ammonia was evident.

Observation 2: Manuralator could hardly mix this manure and flow was very inconsistent.

PHASE 5

		Environmental Conditions		Temperatures		
RUN #	32-34	Temperature	10.2 °C	Run 32	Run 33	Run 34
Run #32 @ 10% QL				20.1	22.2	25.1 °C
Run #33 @ 15% QL		Pressure		T1		
Run #34 @ 20% QL				T2	24.4	25.9
Date	12/28/2003	Humidity	29%	T3	27.9	29.8
Elapsed Time	7 hrs				33.1	°C
Auger Speed	19			Manure	9.8	9.9
Residence Time	3:50			pH	6.6	9.9 °C
				Product	40.1	44.3
				pH	11.9	12.1
				Air	10.2	10.3
					10.5	°C
				NH3 balance		
				Run 32	Run 33	Run 34
<u>Flow Rates</u>				in	1407.6	1407.6
Manure	425 g/min			out	1362.0623	1341.0788
Quicklime	41.3 64 85.5 g/min			captured	31	37.6
				unaccounted	14.5377	28.9212
				Reduction	2.2023302	2.67121341
					3.687127	%
Trap Gas	Run 32 Run 33 Run 34					
	9 9 9 ft ³ /min					

	Ammonia per minute			accounting for dilution to sample bottle							
	Run 32	Run 33	Run 34	Run 32	Run 33	Run 34	Run 32	Run 33	Run 34		
Acid Trap #1	5.1	5.4	6.9	2.55	2.7	3.45	mg NH3	0.02833333	0.03	0.0383333	mg/l air
Acid Trap #2	10.5	13.3	16.9	5.25	6.65	8.45	mg NH3	0.05833333	0.0738889	0.0938889	mg/l air
Acid Trap #3	15.4	18.9	28.1	7.7	9.45	14.05	mg NH3	0.08555556	0.105	0.1561111	mg/l air
	Run 29	Run 30	Run 31	Run 29	Run 30	Run 31					
Raw	3312	3312	3312	63.8	63.8	63.8					as is
Product	2921	2876	2736	49.53	47.51	46.78					
	per kilogram			adjusted for MC							
Raw	9149.171271	9149.17127	9149.17127	63.8	63.8	63.8					
Product	5787.596592	5479.13888	5140.92446	49.53	47.51	46.78					
	per kilogram manure			Adjusted for ql dilution							
Raw	9149.171271	9149.17127	9149.17127	63.8	63.8	63.8					
Product	6366.356251	6301.00972	6169.10936	49.53	47.51	46.78					
	NH3	NH3	NH3	mc	mc	mc					

NOTES

This set of experiments was conducted to discern the benefit of adding insulation to the auger reactor to increase reaction temperature. Medium moisture manure was tested against doses of 10, 15, and 20% quicklime.
 density = 1.0
 Observation 1: Outer cshell of auger detected as same temperature as atmosphere at the level of 0.1 degree celsius.
 Observation 2: Product " appeared " more moist than other similar testes with same MC of the manure.

Units Run ID	Variable	residence time min	Manure flow g/min	MC raw %	dry manure in g/min	solids flow out g/min	MC Product %	Air flow ft3/min	Quicklime flow g/min	Quicklime Dose %	NH3 volatilized mg/min	NH4 volatilized ug/min /g dry solids
11	air flow	5.23	522	63.8	189	575	53.1	0.75	53	10.2	2.05	10.85
12	air flow	5.23	527	63.8	191	579	53.2	2.25	52	9.9	3.95	20.71
13	air flow	5.23	529	63.8	191	582	53.1	9	53	10.0	13.17	68.77
14	Dose	5.17	475	63.8	172	523.1	55.2	4	48.1	10.1	14.2	82.58
15	Dose	5.17	485	63.8	176	558	52.6	4	73	15.1	16.65	94.83
15b	Dose	5.17	487	63.8	176	583.2	49.8	4	96.2	19.8	22.57	128.02
16	mixing	3.83	525	63.8	190	577.6	53.1	9	52.6	10.0	24.19	127.28
17	mixing	3.83	522	63.8	189	575.2	53.1	9	53.2	10.2	29.53	156.27
18	mixing	3.83	526	63.8	190	579	52.9	9	53	10.1	37.29	195.84
19	Jog	7.23	528	63.8	191	582.1	51.6	9	54.1	10.2	36.57	191.33
20	Dose	4.17	422	76.5	99	465	60.5	9	43	10.2	27.05	272.76
21	Dose	4.17	425	76.5	100	490.1	54.6	9	65.1	15.3	41.67	417.22
22	Dose	4.17	430	76.5	101	516	47.7	9	86	20.0	49.62	491.04
23	air flow	5.17	281	76.5	66	309.4	59.0	9	28.4	10.1	16.67	252.44
24	air flow	5.17	282	76.5	66	310.9	54.0	12	28.9	10.2	29.37	443.19
25	air flow	5.17	286	76.5	67	315.5	50.9	15	29.5	10.3	32.28	480.29
26	Dose	3.33	285	76.5	67	327	46.8	9	42	14.7	14.23	212.47
27	Mnaure Temp	3.03	299	63.8	108	328.9	52.2	9	29.9	10.0	28.65	264.69
28	Mnaure Temp	3.03	302	63.8	109	331.5	51.6	9	29.5	9.8	31.15	284.93
29	Dose	2.75	302	51.6	146	332.7	49.5	9	30.7	10.2	1.88	12.86
30	Dose	2.75	300	48.6	154	345	47.5	9	45	15.0	2.72	17.64
31	Dose	2.75	304	48.3	157	364	46.8	9	60	19.7	3.8	24.18
32	Insulated	3.67	425	63.8	154	467.1	52.6	9	42.1	9.9	15.5	10.75
33	Insulated	3.67	428	63.8	155	491	48.7	9	63	14.7	18.81	12.10
34	Insulated	3.67	427	63.8	155	512.1	44.7	9	85.1	19.9	26.52	17.15

Sample Calculations For Heat Balance Sample Run # 15

Heat Change for Manure

$$\Delta H_{\text{Manure}} = \text{MF}_{\text{Manure}} * C_{p_{\text{manure}}} * \Delta T$$

$$\Delta T = (T_{\text{in}} - T_{\text{out}})$$

$$C_{p_{\text{Manure}}} = f_o C_{p_o} + f_w C_{p_w} + f_m C_{p_m}$$

f_o = organic volumetric fraction

f_w = water volumetric fraction

f_m = mineral volumetric fraction = 0

$$\Delta H_{\text{Manure}} = 485 \text{ g / min} * 3.58 \text{ J / g } ^\circ\text{C} * (4.35^\circ\text{C}) \quad \Delta T = 3/2(T_1 - T_3)$$

$$\Delta H_{\text{Manure}} = - 7563 \text{ J / min}$$

$$C_{p_{\text{Manure}}} = 0.362 * 4.2 \text{ J/g } ^\circ\text{C} + 0.638 * 2.0 \text{ J/g } ^\circ\text{C}$$

$$C_{p_{\text{Manure}}} = 3.58 \text{ J / g } ^\circ\text{C}$$

Heat Change for Calciumoxide (CaO)

$$\Delta H_{\text{CaO}} = \text{MF}_{\text{CaO}} * C_p * \Delta T \quad \Delta T = (T_{\text{in}} - T_{\text{out}})$$

$$\Delta H_{\text{CaO}} = 73 \text{ g / min} * - 0.647 \text{ J / g } ^\circ\text{C} * 4.35^\circ\text{C}$$

$$\Delta H_{\text{CaO}} = - 205 \text{ J / min}$$

Heat Change for Air

$$\Delta H_{\text{Air}} = \text{MF}_{\text{Air}} * C_p * \Delta T \quad \Delta T = (T_{\text{in Air}} - T_{\text{out Air}})$$

$$\Delta H_{\text{Air}} = 330 \text{ g / min} * 1.130 \text{ J / g } ^\circ\text{C} * (12.4 - 21.6)^\circ\text{C}$$

$$\Delta H_{\text{Air}} = - 3441 \text{ J / min}$$

Ammonia Volatilization (MF indicates molar flow in this instance)

$$\Delta H_{\text{volatilization NH}_3} = \text{MF}_{\text{NH}_3} (\underline{H}_v \text{NH}_3)$$

$$\Delta H_{\text{volatilization NH}_3} = 9.79\text{E-}04 \text{ g / min} * - 33400 \text{ J / mol}$$

$$\Delta H_{\text{volatilization NH}_3} = - 33 \text{ J / min} \quad (\text{This amount is insignificant to the heat balance})$$

Water Volatilization - The heat required to volatilize water not accounted for in the product and required for hydration for of CaO to Ca(OH)₂. Equally, The amount of heat absorbed by the system through condensation is seen as a heat source.

$$\text{MF}_{\text{H}_2\text{O Volatilization}} = \text{MF}_{\text{H}_2\text{O in Manure}} - \text{MF}_{\text{H}_2\text{O in Product}} - \text{MF}_{\text{H}_2\text{O required for Hydration}}$$

$$\Delta H_{\text{Volatilization / condensation H}_2\text{O}} = \text{MF}_{\text{H}_2\text{O Volatilization}} * (\underline{H}_v \text{H}_2\text{O})$$

$$\Delta H_{\text{Volatilization / Condensation H}_2\text{O}} = 0.42 \text{ mol / min} * 4660 \text{ J / mol}$$

$\Delta H_{\text{Volatilization / Condensation H}_2\text{O}} = 1953 \text{ J / min}$ (Because water is gained by the system, Condensation appears to have occurred for this trial and net volatilization of water is considered zero.)

Natural Convective Diffusion

(Geankoplis, 1993 – pp 256)

$$h = 1.32((T_{\text{pipe}} - T_{\text{air}})/D)^{0.25} \quad \text{W/m}^2 \cdot \text{C}$$

Diameter (D) in meters

$$\Delta H_{\text{Convection}} = q = A * h * (T_{\text{pipe}} - T_{\text{air}})$$

Surface Area (A) in meters

$$\Delta H_{\text{Convection}} = 2.19 \text{ m}^2 * -1.56 * 0.30 \text{ }^\circ\text{C}$$

$$\Delta H_{\text{Convection}} = -31.52 \text{ W} = -31.52 \text{ J / s}$$

$$\Delta H_{\text{Convection}} = -1891 \text{ J / min}$$

Heat of Hydration for Run # 15 - Heat sinks are shown in paranthesis

$$0 = \Delta H_{\text{Hydration}} + \Delta H_{\text{Condensation}} + (\Delta H_{\text{Convection}} + \Delta H_{\text{Volatilization NH}_3} + \Delta H_{\text{Volatilization H}_2}) + \Delta H_{\text{Manure}} + \Delta H_{\text{CaO}} + \Delta H_{\text{Air}}$$

$$\Delta H_{\text{Hydration}} = -1953 \text{ J / min} - (-1891 \text{ J / min} - 33 \text{ J / min} - 0 \text{ J / min} - 7563 \text{ J / min} - 205 \text{ J / min} - 3441 \text{ J / min})$$

$$\Delta H_{\text{Hydration}} = 11182 \text{ J / min}$$

Hydration Efficiency (HEM) on a per minute basis

$$\text{HEM} = 100 \% * \text{Quicklime hydrated} / \text{Quicklime added}$$

$$\text{Quicklime Hydrated} = \text{Molecular weigh of CaO} * \text{Heat of Hydration} / \text{Molar Heat of Hydration}$$

$$\text{Quicklime Hydrated} = 56 \text{ g / mol} * 11166 \text{ J / min} / 65180 \text{ J / mol}$$

$$\text{Quicklime Hydrated} = 9.59 \text{ g / min}$$

$$\text{HEM} = 100 \% * 9.59 \text{ g / min} / 73 \text{ g / min}$$

$$\text{HEM} = 13.16 \%$$

Part 5

Run #	Variable	Manure Temp @ 0	Air temp in	Air temp out	Avg ext pipe temp	Avg int pipe temp	T1	T2	T3	Tp	Average Tpipe-Tair
11	air flow	7.1	7	12.1	7.4	12.1	11.3	12.1	12.9	19	0.4
12	air flow	7.1	7	11.6	7.3	11.6	10.9	11.6	12.4	18.9	0.3
13	air flow	7.2	7	11.2	7.1	11.2	10.3	11.3	12	18.9	0.1
14	Dose	10.9	12.4	21.0	12.5	21.0	19.4	20.7	22.9	31.9	0.1
15	Dose	11.0	12.4	21.6	12.7	21.6	20.5	21	23.4	34	0.3
15b	Dose	11.0	12.5	25.3	12.8	25.3	22.9	23.4	29.5	40.8	0.3
16	mixing	9.7	9.7	18.0	9.8	18.0	17	18.1	19	21	0.1
17	mixing	9.8	9.7	19.0	9.9	19.0	17.9	18.9	20.1	22.4	0.2
18	mixing	9.8	9.8	19.6	10	19.6	18.3	19.4	21	24.1	0.2
19	Jog	9.9	10.2	21.3	10.4	21.3	18.7	21.5	23.8	29.8	0.2
20	Dose	9.8	11.4	22.0	11.5	22.0	19.8	22	24.1	36.6	0.1
21	Dose	9.8	11.4	22.7	11.6	22.7	19.9	23	25.1	47.8	0.2
22	Dose	9.8	11.4	24.8	11.7	24.8	20.1	25.2	29.2	58.1	0.3
23	air flow	9.9	9.9	21.5	10.1	21.5	19.8	21.2	23.4	34.1	0.2
24	air flow	10.0	9.9	18.4	10.1	18.4	17.5	18.1	19.6	29.8	0.2
25	air flow	10.2	9.9	16.9	10	16.9	15.3	17.1	18.4	28.4	0.1
26	Dose	12.4	12.4	22.0	12.6	22.0	19.4	22.6	24.1	51.4	0.2
27	Heated manure	16.1	12.1	26.9	13	26.9	25.1	26.9	28.6	50.4	0.9
28	Heated manure	26.0	15.1	31.6	16.3	31.6	29.8	31.3	33.6	60.6	1.2
29	Dose	9.8	9.4	11.9	9.5	11.9	11.1	12.1	12.4	20.1	0.1
30	Dose	9.9	9.5	14.4	9.6	14.4	12.1	14.7	16.3	21.2	0.1
31	Dose	10.0	9.5	16.2	9.6	16.2	12.4	17.1	19.2	24.7	0.1

Part 5	Variable	Heat	Heat	Heat change			Heat of	convective	Heat of	fractional
		Water	NH3	manure	quicklime	air	Mixing	loss	hydration	hydration
		Volatil	Volatil							
11	air flow	-2764	-4.0	-4491	-82	-158	0.8	-1122	8623	14.0
12	air flow	-2973	-7.8	-4250	-76	-432	0.9	-949	8688	14.4
13	air flow	-2958	-25.9	-4835	-87	-1565	0.9	-654	10126	16.4
14	Dose	301	-27.9	-8939	-163	-3205	0.8	-1338	13374	23.9
15	Dose	1953	-32.7	-7563	-205	-3441	0.8	-1891	11182	13.2
15b	Dose	2757	-44.4	-17282	-616	-4758	0.8	-2615	22560	20.1
16	mixing	-2950	-47.6	-5646	-102	-3106	0.8	-1297	13149	21.5
17	mixing	-2720	-58.1	-6175	-114	-3454	1.7	-1715	14237	23.0
18	mixing	-3174	-73.3	-7636	-139	-3640	2.2	-1807	16473	26.7
19	Jog	-4948	-71.9	-14479	-268	-4150	0.9	-2060	25977	41.3
20	Dose	-7167	-53.2	-10345	-179	-3938	0.7	-1644	23328	46.6
21	Dose	-9477	-81.9	-12599	-329	-4199	0.7	-2085	28771	38.0
22	Dose	-14284	-97.6	-22307	-760	-5007	0.7	-2751	45207	45.2
23	air flow	-6030	-32.8	-5767	-99	-4311	0.5	-2141	18381	55.6
24	air flow	-9981	-57.8	-3376	-59	-4224	0.5	-1573	19272	57.3
25	air flow	-12613	-63.5	-5054	-89	-4369	0.5	-1095	23283	67.8
26	Dose	-13330	-28.0	-7636	-192	-3591	0.5	-1783	26559	54.3
27	Heated manure	-2451	-56.3	-5627	-102	-5504	0.5	-3980	17720	50.9
28	Heated manure	-3143	-61.3	-6171	-109	-6138	0.5	-4770	20391	59.4
29	Dose	4847	-3.7	-1989	-39	-919	0.5	-384	-1512	-4.2
30	Dose	8424	-5.3	-6287	-183	-1814	0.5	-757	623	1.2
31	Dose	11082	-7.5	-10298	-396	-2510	0.5	-1048	3178	4.6

@ 500 g/min

Part V BATCH TESTS

Time min	Ribbon mixer 10% Quicklime			15% Quicklime			20% Quicklime			NH3	
	pH	Temp C	NH3 ww basis	pH	Temp	NH3 ww basis	pH	Temp	NH3 ww basis	mg/l	
0	6.8	9.5	2850	6.8	9.6	2850	6.8	9.8	2850	mg/l	
2	8.9	20.1		9.1	22.4		9.5	23.7			
4	10.3	22.2		10.6	29		11.5	40.6			
6	11.6	22.7		11.9	35.6		12	44			
8	12.2	23.4		12.2	38.4		12.3	48.8			
10	12.2	23.9		12.3	40.7		12.4	50.5			
15	12.2	23.8		12.3	40.7		12.4	50.2			
20	12.3	22.5		12.3	39.2		12.4	49			
25	12.3	21.9		12.3	38		12.4	47.4			
30	12.3	21.3		12.3	36.4		12.4	45.8			
35	12.3	20.7		12.3	35.1		12.4	44.4			
40	12.3	20.2	2426	12.3	34.3	2010	12.4	43.2	1487	mg/l	
	% reduction		14.87719	%		29.4736842	%		47.8245614	%	

	MC
RAW	75.61
10% Product	62.4
15% Product	55.3
20% Product	51.19