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**AN ANALYSIS OF ALTERNATIVE TECHNOLOGIES FOR THE REMOVAL OF
ETHYLENE FROM THE CELSS BIOMASS PRODUCTION CHAMBER**

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ABSTRACT

A variety of technologies were analyzed for their potential to remove ethylene from the CELSS Biomass Production Chamber (BPC). During crop production (e.g., lettuce, wheat, soybean, potato) in the BPC ethylene can accumulate in the airspace and subsequently affect plant viability. The chief source of ethylene is the plants themselves which reside in plastic trays containing nutrient solution. The main sink for ethylene is chamber leakage. The removal technology can be employed when deleterious levels (e.g., 50 ppb for potato) of ethylene are exceeded in the BPC and perhaps to optimize the plant growth process once a better understanding is developed of the relationship between exogenous ethylene concentration and plant growth. The technologies examined were catalytic oxidation, molecular sieve, cryotrapping, permanganate absorption, and UV degradation. Upon analysis, permanganate was chosen as the most suitable method. Experimental data for ethylene removal by permanganate during potato production was analyzed in order to design a system for installation in the BPC air duct. In addition, an analysis of the impact on ethylene concentration in the BPC of integrating the Breadboard Scale Aerobic Bioreactor (BSAB) with the BPC was performed. The result indicates that this unit has no significant effect on the ethylene material balance as a source or sink.

SUMMARY

Several technologies were examined in order to find a suitable method for removing ethylene from the CELSS BPC when detrimental levels are present. For example, during a normal potato growth cycle ethylene levels are usually in the 20 -40 ppb range, therefore, when levels reach the 50-60 ppb range a removal process is initiated. The process consists of placing 200 grams of a material containing potassium permanganate near the air supply duct inside the chamber after which the ethylene concentration is logged on a portable gas chromatograph. When normal levels are reached the permanganate is removed from the chamber. This currently takes several days and is unsafe because the material can be hazardous for both humans and plants. An alternative approach would include the placement of a removal system in the air duct surrounding the chamber so as to eliminate entry into the chamber. Such a removal system would have to meet several design constraints including the avoidance of significant upset to chamber temperature, pressure, humidity, and carbon dioxide levels. In addition it would have to be safe, reliable, and cost efficient. For this purpose four different technologies were analyzed for potential application along with consideration for modification of the existing technique. The four methods examined were catalytic oxidation, molecular sieve, cryotrapping, and UV degradation. None of these methods were acceptable, in part due to their propensity to upset conditions in the BPC. As a result potassium permanganate was explored in further detail beginning with an analysis of ethylene removal during potato growth in May, 1995. Using the material balance model developed by the author in 1994, it was determined that the removal rate is about one half a ppb per hour. This rate was then used for scale up to larger amounts removed as well as faster rate of removal. Four kilograms of permanganate material might be adequate to bring ethylene down to a safe level within an eight hour time period for most conditions encountered in the BPC. In addition an analysis was done to determine whether or not the Breadbord Scale Aerobic Bioreactor contributes in a significant manner to the total ethylene material balance. An upper limit of less than one ppb per day coming from the BSAB was calculated which can safely be neglected in the total balance equation. Finally, recommendations for future experiments were made in an effort to establish whether plants respond autocatalytically during the normal growth phase, i.e., whether exogenous levels of ethylene promote the production of ethylene. Should this be the case, then a control system for ethylene might be employed to optimize the plant growth process.

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I. Introduction

When different crops are produced in the CELSS BPC, the plant hormone, ethylene is produced as well, albeit at different rates throughout the plant cycle. When the production rate of ethylene exceeds the chamber air leakage rate ethylene accumulates in the BPC at parts per billion levels. Conversely, when the leakage rate is greater than the production rate the chamber concentration declines. In a closed and sealed BPC there is always the potential to generate a deleterious level of ethylene. In the case of potatoes 50 ppb might be problematic, therefore, a removal procedure is currently initiated when the concentration reaches this level in order to avoid possible effects on crop viability.

The current removal method involves the placement of approximately 200 grams of pellets containing potassium permanganate inside the chamber near the air supply duct. The permanganate is hazardous (to both humans and plants) and if spillage occurs, especially into the circulating nutrient solution, the plants could be affected. A better, and probably more effective way of removing ethylene when necessary, would involve a system remote to the BPC, i.e., one that could be installed in the surrounding air duct and activated when needed. For this purpose several different technologies were analyzed in the hope of replacing the current procedure.

The following technologies were considered as alternates to the current method:

- 1) catalytic oxidation
- 2) molecular sieve
- 3) cryotrapping
- 4) UV degradation

Each technology was analyzed with respect to design constraints imposed on the system and further analysis of a workable method was performed.

In addition, an analysis of the Breadboard Scale Aerobic Bioreactor's contribution to ethylene concentration in the BPC was made in a similar manner to the analysis of sources and sinks for a material balance model established by the author in 1994.

II. Ethylene Dynamics

In 1994 the author established a material balance model for ethylene in the BPC air space. A primary assumption in the model is that the ethylene concentration in the air space is uniform throughout the BPC, i.e., any ethylene that is of-gassed from the plants is instantaneously distributed throughout the entire airspace. This assumption is premised on the hefty air circulation rate in the BPC (~4 volume changes per minute). It was determined that on a daily average basis there is only one significant source (plants) and one significant sink (leakage) for the determination of the accumulation rate. The accumulation rate was obtained from the first derivative of the concentration curve and the leakage rate was estimated independently from carbon dioxide decay experiments when no plants were in the BPC. The plant production rate was obtained by adding the leakage rate to the accumulation rate and was in agreement with other studies on ethylene production.

Plants produce ethylene at different rates at different stages in the production cycle and the process is not fully understood. One aspect that is particularly important to the BPC is whether or not the plant production rate is dependent on the exogenous concentration since the rate increases with increasing concentration until perhaps some trigger (concentration?) causes the production rate to fall below the leakage rate and the chamber concentration begins to decline. In fact there is evidence (1) of autocatalytic behavior (autoinhibition is also possible) for some plants. On the other hand the increased production may be an endogenous response and may correlate with some plant growth characteristic such as leaf area, etc. Of course to make matters more complicated, both mechanisms could be at play at different times or even at the same time. If only one mechanism is at play it could be determined by dosing the chamber or leaking the chamber during normal plant growth and measuring the ethylene concentration for several hours afterwards. If the rate of production increases in the dosing experiment or decreases in the leakage experiment then the exogenous mechanism is at work. Of course, the dosing experiment would have to be carried out very carefully (small, but significant amounts) so as not to trigger any other response mechanism. If the exogenous mechanism prevails it is possible that adjusting the exogenous concentration could optimize biomass production.

In either case it is important to avoid abnormally high levels of ethylene in the BPC since there are a variety of negative effects that can ensue. In this regard it is imperative to have a reliable removal system.

If exogenous concentration drives production it is most likely a first order process since both accumulation and leakage are first order and a mechanism might be the following:



Net Reaction: Ethylene + ACC > 2 Ethylene * = activated enzyme

The reaction rate, r , = k [Ethylene] [ACC] or if ACC is in excess: $r = k$ [Ethylene]

III. Removal System Design Constraints

The removal system will be located in the air circulation duct surrounding the BPC. The air circulation rate is 400,000 liters per minute so pressure drop should not be a problem; nevertheless, the removal system must not significantly affect the air circulation rate. This high flow rate is advantageous to any removal system since it will most likely eliminate any mass transfer resistance, i.e., the ethylene in the gas phase will be transported very rapidly to the surface of any removal system.

A very important constraint is that there be no significant upset to chamber conditions. The following conditions need to be maintained:

- a) Temperature~ 20-25 C
- b) Pressure ~ 1 atm
- c) Relative Humidity ~ 70-90 %
- d) Carbon Dioxide Concentration ~ 1200ppm

The removal system should be able to reduce the ethylene concentration at a high enough rate to bring the concentration down to a normal level within an eight to ten hour period. Of course the system should be safe, reliable, and preferably low in cost.

Because of the high air flow rates in the BPC air duct it is important to have a removal system which , if porous, maintains its structure under flow. If the material collapses or gets compressed or altered such that the surface area is reduced this could have an effect on the removal efficiency.

IV. Candidate Technologies for Ethylene Removal

Several technologies were examined in an effort to find a suitable method for lowering ethylene concentration in the BPC when levels become problematic for a particular crop. With the exception of cryotrapping, each method has been used to scrub ethylene and literature data is available. First and foremost the technology was analyzed with respect to the design constraints. In most cases the literature data was obtained for small scale laboratory equipment and/or higher ethylene concentrations than those found in the BPC. Nevertheless an attempt was made to extrapolate to the BPC. Each method is presented in detail below.

4.1 Catalytic Oxidation

In a 1978 study Eastwell et al. (2) flowed a compressed air stream containing 20 ppb of ethylene and other hydrocarbons through a 45 cm long, 1.27 cm diameter tube containing platinum on asbestos fibers (5 w/w%) at 800 ml/min. The temperature was maintained at 650 C and all the ethylene was oxidized. The corresponding length of similar catalyst material upon scaleup to the BPC air duct would be 24 meters. This amount of catalyst is much higher than what is most likely required for two reasons. Firstly, a much higher weight fraction of platinum on a surface could be employed and secondly, the high concentration of the other hydrocarbons (ppm range) in Eastwell's study would not be present in the BPC. On the other hand the high temperature would preclude this technique in the BPC because it would cause a major upset.

Abeles (1) describes a Swingtherm catalytic converter which handles 10,000 liters of air (containing ppb levels of ethylene) per liter of catalyst per hour. When scaled to the BPC air duct this would require 3-4 meters of catalyst, a rather large amount. Although this system operates at much lower temperature (~200 C) it would still be prohibitive due to BPC upset capability. This technology could be employed outside the BPC as a free standing, portable unit which could draw the duct air as a bypass stream; however, the effluent to be returned to the BPC would have to be cooled and cost would be a definite factor.

Another problem with catalytic oxidation is that most, if not all of the ethylene would be removed (a finite amount of ethylene is probably good for crop production) if the system were within the air duct at current flow rates. Thus, the bypass technology (lower flow rates than in the air duct) might be the preferred approach with regard to the achievement of an optimum level of ethylene. On the other hand it will be difficult to match any arrangement with a desired level of reduction (a variable target).

4.2 Molecular Sieve

Jiang et al. recently flowed (1cc/min) a mixture of ethylene (8.5 mole %) and ethane through a small tube filled with 2-6 grams of Linde 5A Zeolite material at a

temperature of 30 degrees C and a pressure of 1 atm. The ethylene adsorption rate in this experiment was 0.000005 gmoles/min.

It would be difficult to size a molecular sieve for the BPC air duct based on Jiang's data because the concentration driving force and Reynolds number of the flow are so different. Also, the sieve will only be effective when most, if not all, of the water in the air stream is removed, i.e., the manufacturer recommends bone dry air. To make matters worse even carbon dioxide can reduce the efficiency of the sieve.

A thermal cycle would be necessary to restore the sieve after adsorption has taken place, i.e., the sieve adsorbs at low temperature and desorbs at higher temperature. This could be done when the sieve is saturated with ethylene using a swing system.

For the small amount of ethylene that needs to be removed in the BPC (~.001 gmoles) only 1 Kg of material is necessary (based on a scaleup of Jiang's data) and the cost is nominal. However, the water removal pre-stage would cause a major upset to the BPC unless water could be replenished rapidly downstream from the sieve. This would be difficult to accomplish without installing new humidification capability.

4.3 Cryotrapping

This technology would involve a countercurrent heat exchanger with the BPC air on one side and liquid nitrogen (boiling point of -320 F) on the other. The trace organic of interest (in this case ethylene) would desublimiate and freeze out on the surface of the exchanger. There are two reasons why this method is not suitable for the BPC. Obviously there would be a major upset to the BPC which would require a restoration step downstream. Secondly, ethylene is too volatile to capture at its low concentration in the BPC. Based on equilibrium vapor pressure data (4) the equivalent saturation pressure in the BPC at liquid nitrogen temperature is 395 ppb. Since the problematic concentrations of ethylene in the BPC are in the 50-150 ppb range it would be impossible to freeze out the BPC ethylene.

Based on some preliminary data on ethylene concentrations in the shuttle(5) it is entirely possible that ethylene concentrations in human compartments in space could reach higher than 395 ppb even though it is not clear what the source of ethylene was in the preliminary data.

Cryotrapping might be a desirable technology to employ for lunar and martian stations since it could be used to control water and carbon dioxide levels as well as some trace contaminants by taking advantage of local low temperature conditions.

4.4 UV Degradation

The removal of ethylene by ultra violet radiation is accomplished with germicidal lamps at two different wavelengths, 184 and 254nm (6,7,8). The lower wavelength produces atomic oxygen and ozone, while the second generates molecular oxygen from the ozone produced by the first lamp. It is the atomic oxygen which reacts with ethylene. Unfortunately (6) not all of the ozone is reduced and the residual amount can be as high as 1000ppb. This level can be problematic to BPC crops which are sensitive at 100ppb(9). Otherwise this could be a very inexpensive and simple method for removing ethylene. Shorter and Scott flowed air containing 1200ppb of ethylene from a 600 liter chamber at 60 liters per minute through a 100 liter box containing only one UV lamp. Ethylene concentration was reduced to less than 20ppb in about 20 hours. The slope of the concentration curve is very small as the concentration decreases below 100ppb so the removal rate if applied to BPC concentrations would be very small. Therefore, a much greater number of lamps would be necessary to make this method practical. In any event, until a reliable UV method is developed where ozone is maintained below 100ppb while reducing ethylene, this technology is inapplicable. There is brief mention of a new method which produces ozone which in turn is reduced by catalysis (10), however, no data is given regarding ozone reduction. As more information is published on ambient catalysis it might very well become a viable technology.

4.5 Permanganate Absorption

Ethylene reacts with potassium permanganate and water to form ethylene glycol, manganese dioxide, and potassium hydroxide. The stoichiometry is the following:



Heat and acid promote the further oxidation of the glycol. KMnO_4 absorbents have been used successfully to reduce ethylene levels in growth chambers and greenhouses. According to Abeles (1) the chief disadvantages are the need for replenishment (irreversible reaction) and safe disposal. However, the fact that the reaction is irreversible could be advantageous in the BPC air duct simply because the ethylene would be converted and there would be no need, as in a regenerable system, for ethylene disposal. Nor would there be any chance of re-introducing ethylene to the BPC.

The permanganate is bound to an activated alumina substrate and is initially purple in color. Upon reaction the color changes to brown thereby affording a relatively easy means of determining when the material is spent.

Lidster et al. (11) evaluated KMnO_4 as an ethylene remover from apple storages and found the highest removal when the material was arranged in a tubular configuration. The variables that they found to affect ethylene removal were temperature, relative humidity, particle size, pH, and air flow rate. High temperature increased removal

removal whereas high humidity decreased removal. In some cases alkalinity increased removal. Smaller particles and lower flow rates (packing factors?) increased removal.

Permanganate is the current method for ethylene removal in the BPC. The material currently comes in bulk pellet form so it is manually transferred to holding containers (air through) which are placed in the BPC when needed. Because humidity is a factor, the pellets are placed near the air supply prior to the plant trays. Unfortunately, spillage can sometimes occur and permanganate is hazardous to the plants. Also, the chamber has to be opened in order to bring in/remove fresh or spent material. This is an undesirable mode of control, therefore, a method which can operate remote to the plant chamber is desirable. In this regard Air Repair of Stafford, Texas manufactures permanganate in a tubular form consisting of a polypropylene net which houses robust pellets. The pellets are 3.5-5.0% KMnO₄ by weight and contain 15-20% water and are alkaline in pH.

Summary: Of all the technologies considered only the permanganate has the potential (with modification) to meet the design constraints. Therefore, further analysis and scaling was performed for permanganate.

V. Permanganate Removal Experiment

At the beginning of May of this year a potato crop cycle was started in the BPC. About the 15th of the month the ethylene level in the upper chamber increased to about 60 ppb, therefore, 200 grams of pellets containing permanganate were placed in the chamber. The permanganate was removed on the 30th of May after the concentration had dropped to the 15-30 ppb range as measured by a portable gas chromatograph. In order to determine the effectiveness of the permanganate it is imperative to know precisely how much ethylene is lost to the outside by leakage. During this two week time period the chamber was entered on several occasions making it very difficult to estimate the true chamber leakage rate on an hourly or even daily average basis. The reason for this difficulty is the fact that each person entering the chamber does so in a different manner, i.e., some take more time than others to make their entry and/or exit and some close the door completely without sealing the chamber whereas others may leave the door ajar. Fortunately, there was a three day continuous period during the time that the permanganate was employed where the chamber was in a closed and sealed state. In this mode the leakage rate is known to be 10% of the chamber volume per day. The concentration of ethylene during this three day period is plotted in Figure 1 and although the data is highly scattered (this scatter could also be a diurnal ethylene pattern) it appears to exhibit a downward trend. In fact a linear fit to this data has a correlation coefficient of 0.5. Keep in mind that the sampling method involves a single small port through the wall of the chamber which has a volume of 56,000 liters. In other words there could very well be a sizeable boundary layer near the wall where mass transfer of ethylene produced by the plants is significantly different from the inner part of the chamber. Velocity mapping of the chamber might provide some explanation for the variability of the concentration. However, it is the downward trend that is most important for the computation of the removal rate.

VI. Permanganate Removal Rate

The first step in specifying a permanganate removal system for the BPC is the determination of the current removal rate which can be obtained from a material balance model for ethylene (12). For any time period when removal is occurring the balance is the following: $A = P - L - R$, where A is the accumulation rate in ppb of ethylene per hour, P is the plant production rate in ppb/hr, L is the chamber leakage rate of ethylene also in ppb per hour and R, in ppb/hr, is the removal rate. Since the concentration of ethylene is declining during the three day experimental period, the accumulation rate is negative, i.e., deaccumulation occurs and is obtained from the first derivative of the concentration verses time curve which in this instance is a constant (.18 ppb/hr) throughout the concentration decline. The leakage rate, L, for a closed, sealed chamber is 10% of the average daily chamber concentration per day. On an hourly basis this would be $0.1/24 \times C(t)$, where C is ppb and t is in hours. For this experiment the linear fit for C(t) is $C = 34.4 - .18 t$; however, since the other rates in the material balance equation are average rates, C is taken to be an average value for the three day period (.28 ppb). The production rate, P, is obtained from a material balance on potatoes in the BPC for day 23+ in the cycle (12) and is taken as an average value (.37 ppb/hr) for the three day period. The result is the following:

$$-.18 = .37 - .1/24 (28) - R$$

Or R, the removal rate, is equal to .43 ppb/hr.

Another important rate is the speed at which the permanganate gets depleted. As an example, if you remove 20 ppb by permanganate in a drawdown mode then 5 mg of material are exhausted: $20 \text{ ppb} \times 56,000 \text{ liters} \times 1/22.4 \text{ gmoles/liter} \times 2 \text{ moles permanganate} / 3 \text{ moles ethylene} \times 158 \text{ g/mole permanganate} = .005 \text{ grams exhausted per drawdown}$. If a canister of absorbent material contains 200 grams of potassium permanganate then $200/.005 = 40,000$ drawdowns per canister is a best case scenario (other volatile organic compounds in the BPC can react with permanganate). For a crop which has a higher production rate of ethylene or, if faster drawdown is desirable, additional canisters could be employed. However, without knowledge of the exact amount of permanganate in the material employed, the degree of competition from other compounds that react with permanganate, the long term stability of the porous structure, the effect of moisture on pellet characteristics and other factors it is difficult to predict drawdown capacity. Scaleup will also be difficult without knowledge of the different resistances to mass transfer of ethylene to the permanganate surface in comparison with reaction rate.

VII. BSAB Ethylene Analysis

A Breadboard-Scale Aerobic Bioreactor has been integrated into the BPC loop in an attempt to achieve a closed cycle system. A mixed population of microbes digest plant waste in order to generate nutrient solution for the plants. The water for the 120 liter bioreactor is obtained from BPC condensate. Oxygen for the microbes derives from BPC air. A .75 inch diameter line from the BPC air duct feeds a compressor which sparges the air into the bioreactor. The total volume of the BSAB air loop is under 100 liters (negligible in comparison to the BPC's 113,000 liters).

Microbes have the potential to produce and/or consume ethylene, therefore, it is important to investigate what role they play as a source or sink in the total ethylene material balance. According to Abeles (1) ethylene does not appear to play a role in bacterial growth and development. Soil-borne species such as *Mycobacterium paraffinicum* can grow on ethylene whereas ethylene-producing bacteria might promote plant senescence through microbial attack to facilitate bacterial growth. Certain strains of *Pseudomonas solanacearum* associated with the premature ripening of bananas produce ethylene. In fact this species produces one ten billionth of a mole of ethylene per minute for every 10 billion bacteria present. The growth rate of these bacteria is greater than one billion cells per hour and is higher than BSAB populations, nevertheless, it could serve as a good upper bound for an estimate of BSAB ethylene contribution to the BPC.

Current bacterial counts for the BSAB are around one billion per ml. Assuming that the BSAB microorganisms produce ethylene at the same rate as the *Pseudomonas solanacearum* the BSAB production rate would be the following:

$$10^{-10} \text{ gmole ethylene/min}/10^{10} \text{ bacteria} \times 22.4 \text{ liters/gmole} \times \\ \text{chamber}/56,000 \text{ liters} \times 10^9 \text{ parts/billion parts} \times 120 \text{ liters} \times 1000 \text{ ml/l} \times 10^9 \\ \text{bacteria/ml} = .0005 \text{ ppb/min} = .72 \text{ ppb/day}$$

Given that potatoes produce ethylene at 10-20 ppb/day and that the error in this rate is at least 10% (due to ethylene concentration sampling error and leakage rate estimation error) and that the microbial rate is probably an extreme upper limit (especially since the BSAB uses plant waste as a substrate) it is safe to neglect BSAB ethylene in the total material balance.

VIII. Discussion of Results

Of the five technologies considered for reducing ethylene in the BPC only permanganate has the potential to meet the design constraints. The other methods were excluded for a variety of reasons, especially the potential to create a significant upset in BPC conditions. On the other hand, they could be revisited as future research developments warrant.

The permanganate removal rate was estimated to be about a half a ppb of ethylene per hour for 200 grams of material. Two factors need to be considered in determining the amount of material for BPC use; the amount of ethylene to be removed and the removal time. In the potato experiment the level needed to be reduced from about 60 ppb to about 30 ppb; however, for other crops such as wheat, this could be much higher.

A conservative estimate might be the removal of 100 ppb during a 10 hour period, i.e., a removal rate of 10 ppb/hour. For this rate the capacity of the removal system should be 4 Kg based on a constant ratio of mass of permanganate material to removal rate (the constancy of this ratio needs to be confirmed experimentally). Since the 4 Kg should be adequate for a very large number of removal episodes if kept unexposed to BPC air between episodes, the final system design should have the following features:

- 1) can be easily inserted into the duct for long term use
- 2) permanganate remains unexposed when not needed and readily exposed when ethylene removal is required
- 3) can be easily retracted from the duct for inspection (e.g., color change)
- 4) packing characteristics are time independent and resistant to high duct flow rates

IX. Conclusions and Recommendations

- a) The current method for removing ethylene from the BPC during potato production by potassium permanganate absorption has a removal rate of approximately 0.5 ppb per hour.
- b) Catalytic oxidation, molecular sieve, cryotrapping, and UV degradation were deemed unsuitable as alternatives to the current method.
- c) A better way of removing ethylene with permanganate in the BPC might be the proper placement of 4 Kg of material in the air duct surrounding the BPC.
- d) The Breadboard Scale Aerobic Bioreactor is not expected to contribute significantly, if at all, to the total material balance for ethylene in the BPC.
- e) It is important to establish whether plants, during their normal growth period, respond to exogenous ethylene concentration.
- f) Dosing and/or leakage experiments in the BPC might resolve this question.
- g) If plants do respond to ethylene levels in the air space perhaps ethylene can be controlled through pulsing and removal to optimize the production process.
- h) The current method for measuring ethylene concentration using a portable gas chromatograph exhibits variability which may reflect a diurnal cycle or could be due to sampling error.
- i) In this regard it would be advantageous to study BPC air dynamics in more detail to determine the validity of the perfect mixing assumption.
- j) A dry ice (carbon dioxide) drawdown experiment might be a good test of the perfect mixing assumption in the BPC.
- k) Laser spectroscopy may afford an improved method for the measurement of ethylene concentration and should be explored for BPC use.
- l) The dynamics of ethylene removal by permanganate need to be studied experimentally by simulating BPC conditions in a bench scale reactor. Mass transfer/reaction rate data for permanganate materials in a tubular system could be determined for different concentrations of ethylene which could lead to the establishment of a scaleup model.
- m) The BPC (air duct or bypass) is a good test bed for evaluating ethylene removal technologies during periods of closure when the leakage rate is 10%.

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Figure 1. Concentration vs. Time for Ethylene Removal by Permanganate

