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NOVEL DRYING PROCESS USING FORCED AERATION THROUGH A POROUS BIOMASS MATRIX

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NOVEL DRYING PROCESS USING FORCED
AERATION THROUGH A POROUS BIOMASS MATRIX

présenté par: FREI Kenneth Michael

en vue de l'obtention du diplôme de: Maîtrise ès sciences appliquées

a été dûment acceptée par le jury d'examen constitué de:

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DEDICATION

This work is dedicated to my dear wife Angela whose love and support were integral in maintaining my creativity, drive and sanity throughout the entire process.

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RÉSUMÉ

L'élimination de quantités significatives de boues, surtout celles avec un important contenu biologique, représente un défi économique et environnemental pour les usines de pâtes et papiers. Lors de cette étude, un procédé novateur de bioséchage a été analysé. Ce procédé permet l'extraction de l'eau contenue dans les boues pour permettre l'augmentation de leur valeur calorifique et par le fait même, permettre leur combustion dans les chaudières appropriées à cette fin. Le mélange boues/écorces a été asséché en utilisant une aération par convection forcée et le taux d'assèchement a été amélioré en utilisant l'activité métabolique exothermique des microorganismes thermophiles aérobie.

Des tests en laboratoires ont été réalisés pour trois mélanges boues/écorces. Des données ont été recueillies à l'intérieur de la biopile pour examiner la température, l'humidité, la pression, le débit et la masse totale afin de calculer les pertes d'eau et de carbone. Le ratio 1 :0,5 de boues/écorces (base sèche massique) a permis l'obtention des meilleurs résultats soient: des conditions pneumatiques favorables ainsi qu'une augmentation de siccité de 30,5% à 41,6% dans un intervalle de temps de 13 jours. La génération de chaleur à l'intérieur même de la biopile à permis l'atteinte de températures aussi importantes que 65°C. L'augmentation de température a été corrélée avec l'augmentation du taux d'assèchement. Les pertes de carbone, variant entre 5,5% et 18% pour les trois essais, ont aussi été liées à la génération interne de chaleur.

Le procédé de bioséchage étudié a le potentiel d'offrir les avantages suivants : (1) une économie de combustible, grâce à l'augmentation de la valeur calorifique des boues, aussi associée à une réduction du combustible supplémentaire nécessaire à la chaudière (typiquement du gaz naturel et/ou de l'huile), (2) la réduction ou l'élimination de la nécessité d'enfouissement ou d'épandage agricole des boues, et (3) une réduction des gaz à effet de serre en considérant la combustion de biomasse comme étant nulle pour les émissions de CO_2.

Une analyse technico-économique du procédé a démontré que les usines pour lesquelles l'implantation du procédé serait avantageux sont celles qui : possèdent déjà les installations

nécessaires à la combustion de biomasse et à la manutention de cette dernière, celles qui ont l'espace adéquat pour l'implantation de plusieurs réacteurs à proximité des installations existantes de combustion, les usines qui éliminent leurs boues dans des sites d'enfouissement ou par épandage agricole, et/ou celles dont les coûts en combustible sont très élevés. La période de recouvrement des coûts pour l'implantation de ce procédé est de 2,5 ans pour le cas de base et de moins d'un an pour le meilleur des cas.

ABSTRACT

The disposal of large quantities of sludge, especially those with high biological sludge content, present an economic and environmental challenge for pulp and paper mills. In this study, a novel biodrying process was investigated that increases the calorific value of sludge by removing excess moisture, such that the mixed sludge can be combusted in a boiler. The sludge/woodwaste mixture was dried using forced air, and sludge-drying rates were enhanced by the exothermic metabolic activity of aerobic thermophilic microorganisms.

Laboratory tests were conducted for three sludge/woodwaste mixtures. Data were collected throughout the biopile to monitor temperature, humidity, pressure, airflow, and total mass so that moisture and carbon losses in the sludge could be approximated. The 1:0.5 sludge/woodwaste dry mass-ratio resulted in the best drying rate, providing favorable pneumatic conditions, and resulting in increased sludge dryness from 30.5% to 41.6% in 13 days. Heat generation within the biopile raised the temperatures to peak values as high as 65°C, and increased temperature correlated well with increased rate of water removal. Carbon losses were linked to internal heat generation as well, and total carbon losses ranged from 5.5% to 18% over the 3 runs.

This biodrying process can potentially provide several economic advantages to the mill, namely (1) fuel savings due to the increased calorific value of dried sludge, associated with a reduction in supplemental fuel (typically natural gas and/or oil) to the boiler, (2) reduced or eliminated requirement for sludge landfilling or landspreading, and (3) a reduction in greenhouse gas emissions if biomass combustion is considered net-zero for CO_2 emissions.

A techno-economic analysis of the process showed that mills who should most consider this process include those; that already possess woodwaste combustion facilities and related material handling operations, who have space available for multiple biodrying reactors local to existing boilers, who send their sludge offsite for either landfilling or landspreading, and/or who have high fossil fuel costs. The payback period for implementation of this process at the base case mill was about 2.5 years, and the best-case scenarios were found to be less than 1 year.

CONDENSÉ EN FRANÇAIS

Le traitement de boues actives est un procédé de traitement d'eau efficace et est communément utilisé dans l'industrie des pâtes et papiers. Il n'est pas rare pour les usines d'avoir à gérer quotidiennement des excès de 100 tonnes de boues sèches. Les usines ferment leurs systèmes d'eau, séparent et utilisent mieux les fibres vendables dans le procédé plutôt que de les envoyer aux égouts. Puisque la quantité de fibres primaires envoyées au système de traitement diminue, les charges de DBO_5 (associées avec la production de solides biologiques) augmentent avec l'augmentation la production de pâtes et papiers. Cette combinaison d'événements résulte en une augmentation du ratio de boues secondaires. Les boues mixtes avec une importante proportion de boues secondaires sont d'autant plus difficiles à épaissir et ce, surtout à l'aide des presses à vis.

Avec la combustion et l'enfouissement comme méthodes d'élimination les plus fréquemment utilisées, la mise au rebut des boues mixtes est un problème coûteux pour l'industrie. Avec les écorces généralement brûlées dans les chaudières de production d'énergie et une diminution du recours à l'enfouissement comme mode d'élimination, les usines commencent à combiner les boues mixtes des systèmes de traitement d'eau avec des écorces pour permettre la combustion de ces dernières. Une fois séchées au dessus des niveaux critiques de siccité, les boues peuvent être un combustible viable avec un pouvoir calorifique supérieur (Higher Heating Value, HHV) variant entre 18 et 21 GJ/tonne sèche.

Le procédé examiné lors de cette étude est appelé "bioséchage" et est utilisé pour sécher des boues mixtes des usines de pâtes et papiers à des niveaux de siccité économiquement viables et efficacement combustibles dans des chaudières à écorces (environ 50%). Le procédé sèche un mélange de boues et d'écorces par l'intermédiaire d'une aération forcée. Les taux d'assèchement des boues sont rehaussés par une activité microbienne thermophile aérobie naturellement présente dans la biomasse. Pour le concept du procédé examiné, les boues mixtes épaissies sont combinées avec des écorces, utilisées comme agent structurant et le mélange est ensuite mis dans le réacteur.

Ce procédé de bioséchage a plusieurs avantages économiques potentiels tel que (1) une économie de combustible grâce à l'augmentation de la valeur calorifique des boues sèches (associé avec une réduction du combustible supplémentaire, tel le gaz naturel et/ou l'huile), (2) la réduction ou l'élimination de la nécessité d'enfouir ou d'épandre les boues, et finalement (3) dans le cas ou la combustion de la biomasse est considérée comme étant nulle pour les émissions de CO_2, une réduction des gaz à effet de serre.

La convection et la diffusion représentent les principaux mécanismes par lesquels l'humidité est transportée dans la matrice de biomasse. La convection est reliée à la température, l'humidité et le débit du gaz porteur (air) au travers de la matrice poreuse, tandis que la diffusion de l'intérieur même des particules de biomasse est contrôlée par la température et le gradient de concentration d'humidité.

L'activité biologique aérobie est essentielle au succès du procédé de bioséchage proposé. Les conditions nécessaires à une bonne activité biologique incluent la plage de températures appropriées ainsi que la présence adéquate d'air, d'humidité et de nutriments.

La plage de températures idéales pour le compostage des boues varie entre 35°C et 65°C. Pour l'extraction d'eau dans le procédé de bioséchage, il est préférable d'avoir des températures les plus élevées possible puisqu'elles créent des conditions favorables à l'activité de microorganismes thermophiles.

En conditions aérobies, la biodégradation requiert un transfert d'oxygène uniforme et suffisant de part et d'autre de la matrice. L'air doit être convenablement diffusée dans la matrice de façon à éviter la formation locale de conditions anaérobies. Dans ce procédé de bioséchage, des quantités importantes d'air sont fournies pour atteindre les besoins de respiration de la masse microbienne et pour transporter l'eau à l'extérieur du réacteur.

Cette étude a examiné la faisabilité du procédé de bioséchage proposé par l'intermédiaire de trois expériences en discontinu (batch). L'objectif de l'expérimentation était de déterminer les caractéristiques de séchage du bioséchage de boues papetières mixtes et d'écorces pour que : des bilans massiques d'eau et de carbone soient complétés, un ratio boues-écorces approprié soit déterminé, des résultats préliminaires concernant la performance globale et le taux d'assèchement du système soient obtenus, et que l'information concernant l'amélioration de l'efficacité opérationnelle et/ou de conception du réacteur soit aussi obtenue.

Les boues mixtes mélangées avec les écorces ont été fournies par une usine de pâtes et papiers intégrée localisée dans le nord du Québec. La production de boues mixtes de cette usine est d'environ 100 tonnes sèches par jour avec une siccité moyenne de 26%. Les boues mixtes sont composées de 70% de boues primaires et de 30% de boues biologiques.

Pour ces expériences, un réacteur de bioséchage de 1 m^3 a été utilisé. Ce réacteur comprend deux conduites localisées d'un côté et de l'autre du réacteur et une troisième localisée au centre. Pour cette configuration brevetée, la conduite du centre pousse et tire l'air de façon alternative pendant que les conduites des côtés opèrent à l'opposé de la conduite du centre.

La température, la pression, l'humidité relative et le débit d'air ont été mesurées dans l'influent et l'effluent gazeux. Un total de 18 points de mesure de pression et 9 points de mesure de température ont été positionnés dans le réacteur. La masse totale du réacteur a été enregistrée à l'aide de cellules de pesage.

Le réacteur a été rempli avec un mélange de boues mixtes et d'écorces pour ensuite être recouvert d'une membrane de plastique dans le but de seller le système pour les bilans massiques. Afin de déterminer l'effet du ratio boues-écorces sur la performance du réacteur, le débit d'air a été conservé à ~25 SCFM (standard cubic feet per minute) +/- 2 SCFM pour chacune des trois expériences.

Le taux d'assèchement a été déterminé de deux façons soit par : une mesure en continu des changements massiques globaux du réacteur par l'intermédiaire des cellules de pesage, et par calculs de bilans massiques d'eau à l'aide des données d'humidités relatives dans l'influent et l'effluent gazeux.

La première méthode inclut la perte de masse de carbone (par l'activité microbiologique) et d'eau (par l'intermédiaire du procédé de séchage), tandis que la deuxième méthode considère uniquement l'extraction d'eau.

Deux méthodes ont été utilisées pour déterminer la perte de carbone, soit par: une mesure de la masse sèche représentative de la matrice en calculant la masse totale initiale et finale de chaque expérience et présumant que toute perte de masse sèche était attribuable à une perte de carbone, et par la différence entre la perte de masse totale (mesurée par les cellules de pesage) et la perte d'eau estimée.

La température de l'air humide à la sortie de la matrice peut être corrélée au taux de perte de masse totale. L'augmentation de la température de l'effluent gazeux (une conséquence de l'activité biologique) a permis l'extraction d'une quantité plus importante d'eau non-liée, par conséquent augmentant le taux de séchage.

La plus importante extraction d'eau et de carbone avec 15,4 kg/jour et de 2,62 kg/jour respectivement, a été notée pour la deuxième expérience. Cette expérience a aussi maintenu une température matricielle plus importante d'environ 43°C, atteignant des maximums allant jusqu'à 65°C. Une augmentation de l'activité métabolique a pour conséquence une augmentation de l'efficacité de séchage du système cependant, cette efficacité doit être pesée contre l'augmentation de la perte de carbone qui réduit le pouvoir calorifique du produit séché.

Des mesures d'humidité ont été prises pour déterminer si les expériences en configuration discontinue pouvaient permettre une uniformité de la masse sèche. Il a été déterminé que la matrice avait séché assez uniformément du haut en bas cependant, la partie inférieure était quelque peu plus sèche pour chacune des trois expériences. Ceci pourrait indiquer que la partie inférieure de la matrice sèche de façon préférentielle du à une résistance moindre du débit d'air et la proximité des conduites d'aération.

Pour assurer un bon contrôle du système et une distribution d'air uniforme au travers de la matrice, la performance pneumatique du réacteur de bioséchage est critique. La Loi de Darcy, qui décrit les écoulements dans un médium poreux, a été appliquée aux éléments pour lesquels la pression différentielle était connue à l'intérieure du réacteur de bioséchage et la force nécessaire au déplacement de l'air à travers une masse précise de matériel a été obtenue. Comme la matrice se ré-humidifie, la perméabilité près des conduites d'extraction d'air diminue.

En résumé, les résultats expérimentaux indiquaient les points suivants :

- Les bilans massiques d'eau et de carbone autour du réacteur de bioséchage ont été fermés avec un niveau de certitude élevé;
- Lorsque le débit d'air est renversé, l'air humide ré-humidifie le mélange boues-écorces séché et ceci a pour effet un renouvellement de l'activité microbiologique et par conséquence une augmentation de la température pour une période de 10-20 heures;

- La période de ré-humidification et l'augmentation de l'activité microbienne sont accompagnées d'une augmentation du taux de perte de carbone de la matrice;
- La ré-humidification de la matrice est plus significative au début des expériences lorsque la matrice est encore très humide;
- Des températures matricielles et d'effluent gazeux plus élevés permettent à l'air saturé de transporter une plus importante quantité d'eau massique et par conséquent permet une augmentation du taux d'assèchement;
- L'effluent gazeux devient saturé lorsque la température matricielle augmente au-dessus d'une valeur seuil d'environ 40°C notée lors de la deuxième expérience;
- Il y a des indications que l'influent gazeux passe préférentiellement par le chemin le plus court, soit entre les entrées et les sorties d'air, et par conséquent sèche préférentiellement la partie inférieure de la matrice;
- Plus la matrice sèche, plus la perméabilité de la matrice augmente dramatiquement, diminuant ainsi la perte de pression de part et d'autre de la matrice et minimisant l'ampleur des chemins préférentiels dans la partie inférieure de la matrice;
- Ces observations permettent d'obtenir plusieurs conclusions qui pourraient permettre une augmentation de la performance du système discontinue:
- Il y a une bonne opportunité d'utiliser des débits d'air plus importants initialement (en maintenant des conditions pneumatiques acceptables), ce qui pourrait réduire le temps de traitement;
- Les pointes de températures ont été notées suite à chaque changement périodique de direction d'air (probablement attribuable à la ré-humidification des boues sèches), et il y avait une relation évidente entre des températures matricielles élevées et le taux d'assèchement. Cette observation indique qu'une augmentation du taux d'assèchement global pourrait être obtenue si le changement de direction de l'effluent gazeux était plus fréquent (approximativement à toutes les 10 heures) pour ainsi maintenir à la fois des températures matricielles et des températures d'effluent gazeux plus élevés.

Une analyse technico-économique d'une opération de bioséchage à pleine échelle a été complétée pour démontrer l'application éventuelle de cette technologie pour l'industrie des pâtes et papiers.

Le coût capital du système de bioséchage a été évalué selon les systèmes suivants: 1) le réacteur de bioséchage, 2) les soufflantes et la tuyauterie, 3) la manutention du matériel, 4) les capteurs d'instrumentation & de contrôle et 5) les coûts capitaux indirects.

Les coûts d'opération et les hypothèses nécessaires à cette étude incluent les items suivants:

Combustibles fossiles: Sans bioséchage, les usines de pâtes et papiers combinent les boues, les écorces et les combustibles fossiles pour atteindre la production ciblée d'énergie en gigajoules (GJ). Suite à l'implantation du procédé de bioséchage, une réduction de la quantité de combustible fossile nécessaire peut être accomplie.

Écorces: Pour le procédé de bioséchage, les écorces sont utilisées comme agent structurant des boues. Il est présumé qu'une fois le procédé de bioséchage implanté, les écorces qui ne sont pas utilisées comme agent structurant continueraient à être brûlées dans la chaudière avec le produit final séché du bioséchage.

Élimination des boues: Le coût associé à l'élimination des boues sans le procédé de bioséchage inclut les coûts liés à l'élimination des boues du site par l'enfouissement et l'épandage agricole. L'élimination des cendres de la chaudière est un coût continu et est inclut car une augmentation de la quantité de boues qui sont brûlées résulte en une augmentation de la production de cendres.

Électricité: Le coût opérationnel primaire pour le procédé de bioséchage est l'électricité nécessaire aux soufflantes.

Réduction des gaz à effet de serre (GES): L'impact attribuable à l'émission des gaz à effet de serre dans l'atmosphère est normalement exprimé par l'émission de dioxyde de carbone équivalent (CO_{2E}). La législation n'est pas encore appliquée mais éventuellement, il est présumé que l'industrie opérera sur un système de crédits pour lequel il faudra acheter les certificats d'émission de GES du gouvernement ou du marché libre.

Le scénario du cas de base a été modélisé pour déterminer la performance et les coûts qui lui sont associés. Cette usine produit 100 tonnes sèches de boues par jour, desquelles 16% sont envoyées au site d'enfouissement et 84% sont brûlées dans une chaudière à écorces existante. Actuellement, le ratio boues-écorces du mélange envoyé à la chaudière est de 1 :3,5. La chaudière à production d'énergie est actuellement soutenue avec en moyenne environ 22,000 m^3/jour de gaz naturel annuellement.

Les hypothèses clés pour le coût capital et les coûts d'opérations incluent les suivantes:

- Le système défini dans le cas de base présume que le mélange boues-écorces d'un ratio de 1:0.5 est séché d'une siccité initiale de 30% à une siccité finale de 50% pour un temps de résidence de 7 jours;
- L'extraction d'eau du mélange boues-écorces a pour effet une augmentation du pouvoir calorifique du mélange et par conséquent, il en résulte une diminution de la quantité de combustibles fossiles nécessaire à la chaudière à production d'énergie pour une même demande énergétique que dans le cas pré-bioséchage;
- Le coût d'enfouissement des boues est donc éliminé mais il y a tout de même une petite augmentation de la quantité de cendres à éliminer par enfouissement puisque le 16% de boues autrefois enfouies sont maintenant brûlées;
- De modestes crédits de CO_2 ont été calculés;
- Il y a une augmentation de la consommation d'électricité, celle-ci étant attribuable au fonctionnement des soufflantes et des convoyeurs mécaniques;
- Une chargeuse frontale est nécessaire pour vidanger le réacteur.

Des économies annuelles des coûts opérationnels de plus de $2 millions sont réalisées dans le cas de base. Lorsque les épargnes sont comparées au coût capital, la période de recouvrement pour le cas de base est d'environ 2 ans et demi.

Une analyse de sensibilité a été complétée pour les multiples paramètres ayant un impact sur la période de recouvrement pour le cas de base. Les résultats de performance qui sont ressortis dans cette étude incluent les épargnes annuelles grâce à l'implantation du procédé de bioséchage, le coût capital global du système, la période de recouvrement et la consommation d'énergie spécifique du procédé.

Il a été déterminé que les quatre paramètres qui ont un impact important sur la performance du système sont: la siccité initiale du mélange, le temps de traitement dans le réacteur, le ratio de boues-écorces, et la température intérieure du réacteur et les pertes de carbone qui lui sont associées.

Plus la biomasse est humide initialement, plus la quantité d'énergie requise pour la sécher à des niveaux de siccité appropriés à la combustion est importante. Le temps de traitement du bioséchage a un impact sur le coût global du système puisqu'un temps de résidence plus long nécessite des réacteurs plus volumineux et plus nombreux. Le ratio boues-écorces a aussi un effet important sur le coût total du système car des quantités plus importantes d'écorces ajoutées à une quantité déterminée de boues résulte en une augmentation du volume total de matériel à traiter. Comme il a été précédemment mentionné, la température de l'effluent gazeux suit celle de la matrice et de l'air plus chaud permet des taux d'assèchement plus élevés. Par le fait même, cela permet de réduire le débit d'air nécessaire pour sécher la matrice pour une période de temps déterminée, ce qui réduit les dimensions et le temps d'opération des soufflantes. Des températures internes plus élevées du réacteur génèrent des taux de consommation de carbone plus élevés. Donc, bien que le taux d'assèchement de la matrice augmente avec des températures plus élevées, le pouvoir calorifique du combustible séché est réduit grâce à l'activité métabolique de la biopile. La consommation d'énergie spécifique diminue avec une augmentation de la température interne. La consommation d'énergie spécifique est d'environ 500 KJ/ kg d'eau extrait est très compétitive lorsqu'elle est comparée à des systèmes tels que les séchoirs rotatifs qui consomment plus de 6 000 KJ/kg.

Basé sur les résultats de l'analyse de sensibilité, trois scénarios ont été développés selon les paramètres clés : le scénario du pire cas, le scénario du meilleur cas et le scénario cas le plus probable. Les scénarios suivants ont été comparés au cas de base :

Pire cas: un temps de résidence important dans le réacteur et une siccité finale de seulement 45%, un faible contenu énergétique des boues et des écorces, un ratio boues-écorces élevé de 1:1, une basse température interne.

Meilleur cas: un temps de traitement court et une siccité finale de 60%, un important contenu énergétique des boues et écorces, un ratio boues-écorces élevé de 1:0,25, une température interne élevée et une courte distance nécessaire à la manutention du matériel par convoyeurs.

Cas probable: semblable au cas de base excepté que les installations de manutention du matériel existent déjà sur le site (aucuns coûts associés à l'équipement de convoyeurs et d'équipement de mélange), un temps de résidence vraisemblable, un contenu énergétique des boues et écorces vraisemblable, ratio boues-écorces vraisemblable (1:0,5), une siccité finale de 55% et une faible température interne.

Dans le premier scénario, l'important temps de résidence et le ratio de boues-écorces élevé résultent en des volumes de matériel à traiter excessivement importants et des temps de traitement plus longs, ce qui nécessite de multiples réacteurs. Les quantités d'écorces nécessaires sont tellement importantes que des quantités supplémentaires doivent être achetées, ce qui a pour effet de réduire les épargnes au niveau des coûts opérationnels. Cela en combinaison avec un coût capital de $14 millions génère une période de recouvrement prohibitive de 16 ans.

Le court temps de résidence du second scénario (3 jours) et le faible ratio boues-écorces (1:0,25) résulte en un volume de matériel à traiter plus petit, ce qui a pour effet de minimiser le nombre de réacteurs nécessaires à un seul avec un second à ses côtés pour le remplissage et le vidange. Une quantité moindre d'écorces est utilisée comme agent structurant et le produit final augmente le pouvoir calorifique à un point tel que tous les combustibles fossiles et la moitié des écorces peuvent être éliminés de la chaudière pour une même production d'énergie que le cas de pré-bioséchage. Ce scénario permet des économies de plus de $5 millions annuellement et représente un coût relativement faible, soit de $3,3 millions. Ce scénario génère donc un projet qui peut être repayé en moins d'un an.

Finalement, le troisième scénario utilise des valeurs initiales plus réalistes et plus semblables à celles du cas de base. La différence majeure entre le cas de base et ce troisième scénario est que ce dernier a des installations déjà sur place et que le coût est déjà considéré dans l'analyse des coûts. Cet arrangement crée une période de recouvrement des coûts d'environ un an.

En plus du cas de base, 9 autres usines hypothétiques ont été modélisées dans le but d'établir l'applicabilité du procédé de bioséchage à l'industrie des pâtes et papiers. Il a été déterminé que l'économie annuelle moyenne est la plus importante pour les usines qui disposent de la quasi-totalité de leurs boues ou la totalité de leurs boues par l'enfouissement et/ou l'épandage agricole. Les usines pour lesquelles des écorces sont déjà présentes sur le site ont aussi des périodes de recouvrement moindre. Il est présumé que toutes les usines modélisées sont capables de brûler de la biomasse dans leurs installations existantes. Il est possible que les usines qui envoyaient leurs boues hors site et qui ne brûlaient pas d'écorces n'aient pas de chaudière à écorces sur place. Si ce manque d'équipement est considéré, il est difficile de justifier le coût de l'implantation d'un système de bioséchage à cause du coût capital important associé à l'installation d'une nouvelle technologie de combustion ou encore à cause des modifications majeures nécessaires à l'adaptation de celles existantes.

Pour maintenir un traitement des boues uniforme et pour éviter le séchage préférentiel de la matrice, un nouveau concept de réacteur de bioséchage en continu a été proposé. Les boues seraient déposées sur le dessus du réacteur et elles descendraient lentement au fond en étant séchées par des écoulements croisés, éliminant ainsi le besoin d'un réacteur de réserve utilisé pendant le remplissage et la vidange du réacteur en opération. L'augmentation de la hauteur permettrait potentiellement de minimiser l'aire de surface. La technologie de chargement et de déchargement du réacteur continu serait semblable à celle utilisée par les usines de pâtes et papiers pour la manutention des écorces. Le coût additionnel le plus significatif pour le système en continu serait une vis de transport, présumée comme étant nécessaire à l'extraction du matériel à cause de ses résultats obtenus pour des opérations de manutention de copeaux et d'écorces. En plus de l'extraction automatique du matériel, le système continu éliminerait le besoin d'une chargeuse frontale requise pour le système en discontinu ainsi que les combustibles nécessaires et le salaire d'un employé.

L'air serait fournie à des débits décroissants tout au long du réacteur et contrôlés par l'humidité relative de l'effluent gazeux (qui serait maintenu à 100%). Des débits d'air plus importants dans la partie supérieure du réacteur transporteraient l'humidité de surface de la matrice et par le fait même conserveraient une température matricielle relativement faible pour ainsi préserver le pouvoir calorifique des boues. Au fur et à mesure que l'eau non-liée serait éliminée, le débit d'air contrôlé serait réduit pour permettre l'extraction d'eau liée par diffusion.

Un procédé novateur de bioséchage a été proposé et la technologie de biopile utilisée précédemment pour le compostage et d'autres applications a été adaptée pour le séchage de boues et d'écorces des usines de pâtes et papiers. Si ce procédé est retenu, il pourrait résoudre un important problème environnemental et économique auquel font face plusieurs usines de pâtes et papiers. Les résultats initiaux sont très prometteurs et de plus, il semble y avoir une opportunité significative pour une nouvelle configuration continue du réacteur.

Une analyse technique et économique du procédé de bioséchage a été complétée pour juger de sa viabilité économique pour divers scénarios d'usines de pâtes et papiers. Les paramètres d'opération qui ont eu un effet significatif sur le procédé sont la siccité initiale du mélange, le temps de résidence dans le réacteur (temps de traitement), la température interne de la matrice et le ratio boues-écorces.

Les usines pour lesquelles ce procédé peut être économiquement attirant incluent celles qui ont déjà des installations de combustion et de manutention du matériel, les usines qui doivent payer pour éliminer leur boues hors-site (par enfouissement ou épandage agricole), celles qui ont l'espace nécessaire à l'implantation de multiples réacteurs de bioséchage, et les usines qui pourraient remplacer l'énergie en provenance combustibles fossiles.

Les coûts capitaux pour un système en discontinu varient entre $3 et $6 millions avec des périodes de recouvrement variant entre 1 et 5 ans. Le réacteur en configuration continu, en considérant les systèmes de charge et de décharge, résulterait en une économie de plus de 20% du coût capital ($2 et $5 million) et une réduction de 33% sur le retour sur investissement (0.5 – 3 ans).

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

Symbol/Abbreviation	Description
A	Area
AST	Activated Sludge Treatment
BOD	Biological Oxygen Demand
CO_{2E}	Carbon Dioxide Equivalent
D	Diameter
d	days
DIP	Deinking Pulp
F_A	Force Required to Move Air Through a Given Mass of Material
GHG	Greenhouse Gases
GJ	Gigajoules
h	Heat Transfer Coefficient
H	Humidity
HHV	Higher Heating Value
K	Permeability
K_e	Effective Permeability
kWhr	Kilowatt hour
k_y	Mass Transfer Coefficient
L	Length/Distance
LF	Landfill
LHV	Lower Heating Value
LS	Landspread
$\dot{m}_x$	Mass Flow
M	Molecular Mass
MJ	Megajoules
MSW	Municipal Solid Waste
n	Porosity
N	Flux of Water Removed from a Solid
P	Pressure
P_A	Partial Pressure of Water Vapour
Pa	Pascals
P_S	Vapour Pressure of Water
Q	Volumetric Flowrate
q	Rate of Convective Heat Transfer
R	Rate of Water Removal or Universal Gas Constant
r	Radial Distance
Re	Reynolds Number
REV	Representative Elementary Volume
rH	Relative Humidity
SCFM	Standard Cubic Feet per Minute

SEC	Specific Energy Consumption
SS	Stainless Steel
T	Temperature
t	Tonne
TPD	Tonnes per Day
u, v	Velocity along the x and y-axis, respectively
V	Volume
v	Velocity
VOC	Volatile Organic Compounds
W	Watts
X	kg Free Moisture/kg Dry Solid
X_C	Critical Moisture Content
y	Mole Fraction of Water in Air
α	Viscosity of Air
λ_W	Latent Heat of Water
μ	Viscosity
ρ	Density
ρ_b	Bulk Density

LIST OF APPENDICES

1.0 – INTRODUCTION

Activated sludge treatment (AST) is an efficient and commonly used wastewater treatment method employed in the pulp and paper industry. Disposal of mixed sludges from this system is a costly problem for the industry, with combustion and landfilling being the leading disposal methods. Since landfilling is losing favour as a sludge disposal option, more mills are starting to combine bark with mixed sludge from wastewater treatment for combustion in the power boilers, since the sludge is a viable fuel source once dried.

The goal of the biodrying process investigated in this study is to dry mixed pulp and paper mill sludges to levels where they can be economically and efficiently combusted in woodwaste boilers, i.e. approximately 50% solids. The process dries a mixture of sludge and woodwaste using forced aeration. Sludge-drying rates are enhanced by the exothermic metabolic activity of aerobic, thermophilic microorganisms naturally present within the biomass. In the process concept, mixed dewatered sludge from treatment is combined with bark as a bulking agent, and then fed to the biodrying reactor. This results in a process that can dry large quantities of waste biomass using only aeration power. Heat for moisture removal is provided biologically, resulting in an efficient drying system.

This biodrying process can potentially provide several economic advantages to a mill, such as fuel savings due to the increased calorific value of dried sludge, reduced or eliminated sludge landfilling or landspreading, and a reduction in greenhouse gas emissions, since biomass combustion is considered net-zero for CO_2 emissions under the Kyoto Protocol.

The objective of this project is to fully examine the biodrying technology to determine its applicability in the pulp and paper industry. In this thesis, preliminary test results are presented for the novel application of the biodrying process, and the techno-economic feasibility of the process is evaluated. Innovative sludge management solutions such as the biodrying process investigated in this study are important because they do not merely dispose of the problem, but rather, try to extract some benefit from what is otherwise a waste stream.

The investigation of this drying process begins with a literature review describing how biomass wastes are produced in pulp and paper operations and in what quantities as well as the reasons why they pose a challenge to the pulp and paper industry. Further sections describe the existing solutions used for disposal of these wastes. Current disposal techniques are compared and contrasted, followed by a discussion of proven and emerging drying technologies. Specifically, the SmartSoil™ technology is introduced along with the biodrying concept. Finally, the biodrying process investigated in this study is presented and the test results are used to illustrate how it can potentially offer a viable solution for sludge management and disposal.

Batch experiments were conducted on various mixtures of pulp and paper mill sludge and woodwaste in a 1000 L reactor. The goal of these experiments was to characterize the drying parameters and pneumatic performance of a scaled-down biodrying reactor. Based upon analysis of the data from these experiments, recommendations for future laboratory and full-scale applications were made. These experiments test a unique method for efficiently drying biomass at large scale.

The information gathered from the experiments was used to design a likely, real-life system. A technical and economic analysis of this system was carried out to assess whether this novel technology can present the pulp and paper industry with a viable biomass drying solution.

2.0 – SLUDGE & BIOMASS MANAGEMENT IN THE PULP & PAPER INDUSTRY

The pulp and paper industry is a large consumer of natural resources and inevitably generates significant amounts of waste products. Yield optimization and new process technologies will reduce the amount of waste being produced in the long term, but bark and unusable components of the cellulosic raw materials still need to be managed. In this section the biological waste production from mills is characterized, as well as current and emerging waste management options.

2.1 – Sludge Generation and Dewatering

Mills produce, on average, in the order of 60 m^3 of wastewater per tonne of paper produced (Thompson, 2001), which is discharged into the receiving environment. One line of thought proposes that wastewater treatment systems, such as activated sludge treatment, are merely in place as a way of buying time before technology allows for completely closed-loop systems (Hynninen, 1998). However, the transition to closed systems is not going to happen soon except for products that can incorporate lower grade fibre and contaminants such as board mills (Lagacé et al., 2000). Even when these pulp and paper water systems are completely closed, primary and biological sludges will still continue to be generated. These challenges suggest that sludge from activated sludge treatment facilities will remain a problem for some time to come.

2.1.1 Biological Treatment of Pulp and Paper Mill Wastewater

Over the last 25 years, and in particular in the wastewater regulations of 1995-1996, legislations have been passed that require pulp and paper facilities to install secondary (biological) treatment to their wastewater treatment systems. The effect of these systems can be seen by a marked reduction in biochemical oxygen demand (BOD) discharges from pulp and paper mills. Unlike physical treatment processes (filtration, gravity settling, etc.), the primary purpose of these systems is to remove the organic load (dissolved and colloidal) from wastewater streams. The activated sludge process is one of the most common methods used for this purpose (Metcalf and Eddy, 1991). Other common methods include sequencing batch reactors (SBRs) and lagoons or aerated stabilization basins (ASBs).

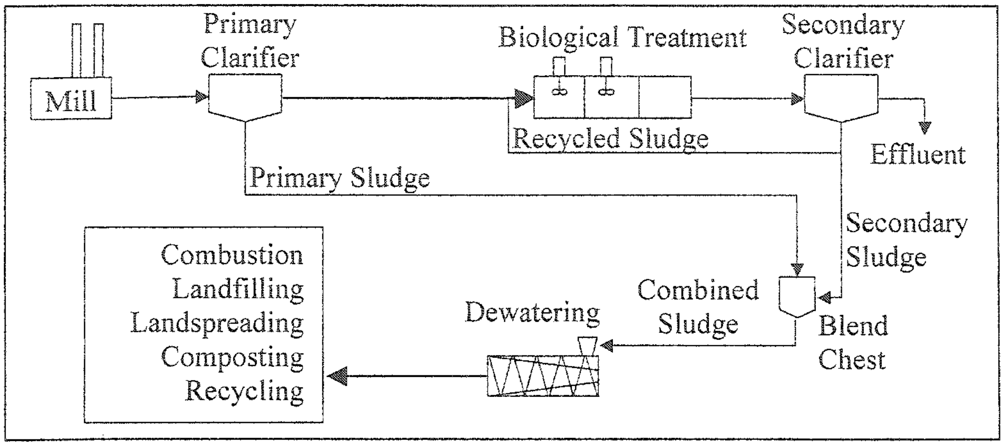

Figure 2.1: Schematic of Wastewater Treatment and Sludge Treatment

Figure 2.1 illustrates the activated sludge treatment (AST) process. First primary solids are removed through flotation or settling in a clarifying step. This produces what is termed "primary solids", which are generally composed of fibres and other cellulosic materials along with any other settleable solid particles from the process (fillers, grit, etc.). This sludge is relatively easy to dewater.

The clarified water is then fed to an aerated basin where biological treatment takes place. Here a resident microbiological community acts to consume the organic components of the wastewater as a food source (BOD), eliminating a large portion (typically > 90%) of the BOD load. The microorganisms produce CO_2 and water as they degrade the waste, but more importantly, they go through their normal life cycle, eventually being extracted as a solid waste stream from the secondary clarifier. A large portion of this cellular mass is recycled (return activated sludge or RAS) to the inlet of the treatment process to maintain microbial population, but a certain amount is wasted from the secondary clarifier in the form of waste activated sludge (WAS) or secondary sludge. Secondary sludge is produced depending on the design and operation of the AST, and typically wasted from treatment in ranges from 40 to 85 kg sludge per tonne of wastewater BOD removed (PAPTAC, 1999). Waste activated sludge is more difficult than primary sludge to dewater to levels appropriate for further handling (i.e. disposal or combustion).

2.1.2 Mixed Sludge Dewatering Challenges

As shown in Figure 2.1, the primary and secondary sludges are typically mixed together in a blend chest prior to dewatering. The sludge ratio is important for the dewaterability of the mixed sludge at the dewatering stage. Typical biological sludge ratios are in the 0.4 range (i.e., containing 40% biological sludge by dry mass). As mills are optimizing their processes, they are closing their water systems and keeping valuable fibre in the process rather than sending them to the sewer. As a result, the amount of primary fibre going to treatment is decreasing. Concomitantly, the rise in paper production levels at mills is causing the dissolved organics concentration in wastewater streams to increase. These trends are leading to less primary sludge and larger quantities of biological sludge being created. Biological sludge ratios over 0.5 are notoriously difficult to dewater, involving high polymer consumption and lower final solids of the mixed sludge (often under 30%).

The sludge dewatering train typically consists of three main components: sludge pre-conditioning, pre-thickening, and thickening (or dewatering). Pre-conditioning involves mixing of the two sludges in the blend tank and at this point or more typically in-line a little further on, polymers are added to the mixture to help coagulate and flocculate the solid particles in the dilute (1-3% solids) stream. The conditioned sludge then goes to a pre-thickening step that typically involves a gravity table or a rotary sludge thickener (RST). These devices bring the sludge mixture from 1-3% to about 8-10% solids content. The two most common dewatering devices used in the industry are belt presses and screw presses. To a lesser degree, vacuum presses, V-presses and centrifuges are also used (NCASI, 1999). Of these, the screw press usually performs the best, dewatering combined sludges to about 40% solids content provided that the biological sludge content is low enough. Belt presses in comparison, typically produce a cake of only 20-25% dryness. Due to inefficient sludge pre-conditioning, non-optimized sludge dewatering operations, and/or difficult (high biosolids content) sludge mixtures, screw presses often achieve far less than 40% solids in practice and often under 30% (PAPTAC, 1999).

Once the sludge has been dewatered, it must be transported for disposal. This process ranges from simply allowing the sludge to fall onto a pad to be removed by front-end loaders to transporting the sludge using conveyor systems that are more capital-intensive, but cheaper to operate than manual removal. In either case, the sludge must be processed in a timely fashion to avoid odour generation and/or re-hydration.

2.1.3 Woodwaste Management at Pulp and Paper Mills

Typical solid waste by-products from pulp and paper mills include bark, knots, sawdust, primary and secondary sludges, off-spec chips and other material unsuitable for pulping. Logging operations involve tree cutting, transport, debarking and chipping for pulping, and there are solid wastes from each of these stages. Bark and woodwaste will often be produced in far greater quantities than the sludge produced from wastewater treatment. In one reported example, a Canadian pulp mill produced four times more dry tonnes of bark than it did sludge (Hepburn, 1994). The supply chain related to wood products can be straightforward for integrated mills that cut, transport and process their own stock or it can be highly inter-related where mills purchase chips, logs and woodwaste from outside sources. With the rising costs of fossil fuels required for steam production in the industry, an energy source such as biomass could represent an important opportunity, but only if it can be obtained economically and with sufficient profit to offset the disadvantages of using it. Some of the advantages of using woodwaste as a fuel source include the low cost (depending on availability), the comparatively low ash content relative to coal, and its "green" characteristics (it is a renewable resource, and burns with lower SO_x and NO_x emissions than fossil fuels). Despite the benefits, there are drawbacks to using biomass as well, such as the often high moisture content (>50%), the non-uniform material characteristics, as well as sand and grit that can become entrained in bark (McBurney, 1993). Combustion is frequently the final disposal technique for woodwaste, but some mills must deal with it in other ways if facilities do not exist for energy conversion on-site, including landfilling, composting and re-sale to other mills or industries.

Transport of woodwaste is often the primary cost associated with using it as fuel. Sometimes the material needs to be purchased, but typically woodwaste production is linked to the mill's activities or to closely related industries such as sawmills. The process becomes uneconomical when the woodwaste needs to be transported more than 150 km from source to boiler (McBurney, 1993). Other characteristics of woodwaste such as calorific value and ash content will be discussed in later sections.

2.1.4 Other Pulp and Paper Mill Residuals

In addition to the biomass (sludge, woodwaste) being generated from mill operations, there can also be a variety of inorganic wastes, especially from mills that have chemical pulping operations. Some of these include: fly and grate ash from the boilers, lime muds, grits, green liquor dregs, metal waste and general garbage (office waste, packing, etc.) (Reid, 1998). Various types of ash are produced from the combustion process in a mill's power boilers. Precipitator and fly ash are produced from the air treatment systems and grate ash is what remains of the solids from combustion. In 1995, over half a million tonnes of ash were produced from Canadian mills (Reid, 1998) and nearly three million in the United States (NCASI, 1999). The higher production in the U.S. is due in large part to coal burning. Coal has an ash content of around 10% (dry weight) and is used extensively in the States, accounting for 46% of the ash generated (NCASI, 1999). Fuels such as oil and natural gas have little to no ash associated with them, while biomass fuels do. Therefore, combustion of biomass may lead to increases in ash production in combustion systems where oil and gas were burned beforehand. Inorganic solid wastes, including ash, are most commonly disposed of through landfilling (Reid, 1998; NCASI, 1999).

2.2 – Properties of Sludge and Biomass Mixtures

Given the variety in pulp and paper making processes, treatment options and sludge qualities, it is clear that there are as many specific characteristics as there are operating scenarios. The following describes some of the general characteristics, including dewatered moisture content, chemical composition, calorific value, and bulk density of the following component materials of the mixed sludge to be dried:

- Pulp Sludge
- Deinking Sludge
- Recycled Paper Mill Sludge
- Woodwaste (Bark)

Table 2.1 summarizes parameters for several types of biomass.

Table 2.1: Biomass Characteristics

PARAMETER	Dewatered Mixed Pulp Mill Sludges	Dewatered Deinking Mill Sludges	Dewatered Recycled Paper Mill Sludges	Woodwaste (Bark)
Number of Mills →	5	2	2	4
References	James, 1991 Nickull, 1991 Durai-Swamy, '91 McBurney, 1993 Kraft, 1993 La Fond, 1997	Kraft, 1993	Durai-Swamy, 1991 Aghamohammadi, 1993	James, 1991 McBurney, 1993 Kraft, 1993
Solids Content (% solids)	36%	42%	48%	52%
Composition				
Carbon (C)	50.6%	30.0%	48.5%	50.2%
Hydrogen (H)	6.2%	3.9%	6.5%	5.8%
Oxygen (O)	32.2%	24.5%	41.5%	40.7%
Nitrogen (N)	3.1%	0.7%	0.5%	0.2%
Sulphur (S)	0.8%	0.2%	0.3%	0.1%
Ash	6.5%	40.7%	2.9%	3.1%
HHV – dry (KJ/kg) (Experimental Values)	21,725	12,112	20,700	20,212
Dulong HHV – dry (KJ/kg)	20,233	11,374	18,257	17,955
Bulk Density (kg/m^3)	400 –700	400 -700	400 –700	250 - 400

Note: Values in Table 2.1 are averages over the "Number of Mills"

2.2.1 Moisture Content

Moisture content describes the total amount of water in the material, including both bound and unbound moisture (see Section 3.1). The total amount of water is determined by weighing a sample, oven-drying it at 105°C to constant weight, and then weighing it again. The final mass is the dry mass, which is divided by the initial wet mass to yield a value in percent solid material. Many use moisture content rather than solid content, but *% solids* will be used in this thesis. The moisture content can be simply calculated by subtracting the % solids from 100%.

2.2.2 Composition and Energy Value

The separate elemental components of a biomass mixture are of interest to quantify the energy value of burning a particular material. By-products such as inorganic content (ash) and heavy metals are important issues for the disposal of the products of combustion. Important parameters often used in combustion include the Higher Heating Value (HHV) and Lower Heating Value (LHV). The HHV takes into account the total energy available from the combustion of the material with air, including the energy recovered from the latent heat of the steam produced during combustion, representing the maximum available energy that can be obtained from a given material (McKendry, 2002). The LHV does not consider this latent heat captured in a modern boiler, therefore HHV will be used in this work. HHV is typically reported in units of energy per dry unit of mass such as KJ/kg, kcal/lb, or GJ/tonne. The heating values of sludge can be determined in two ways, either through the use of a bomb calorimeter for experimental values, or through calculations based on the elemental composition of the sludge. Bomb calorimeters are accurate to about 2%, and give a better idea of the exact nature of any particular biomass fuel source. In addition, they provide the HHV value (Albertson, 1992). One common formula for elemental analysis is the Dulong formula (Hougan and Watson, 1947) that calculates the HHV using the percent composition of carbon, hydrogen and sulphur.

$$Heat\ \ Content(Btu/lb) = 14495 \times C + 61000\left(H - \frac{O}{8}\right) + 5770 \times S \qquad (2.1)$$

Table 2.1 presents experimental and calculated heating values. In general, the experimental values are somewhat higher, due to polymers, oils and greases sometimes found in sludges and therefore not accounted for by Dulong.

2.2.3 Bulk Density

Bulk density is important for the transport as well as the aeration of materials. The bulk density (kg/m^3) is essential for reactor sizing as well as for calculating sludge/bark mixing ratios. Although various pure materials, when packed precisely, will have well-established densities, the bulk density of biomass is more difficult to predict. When biomass is piled, it can settle into several different geometries that are affected by parameters such as moisture content, particle size, piling height (and therefore compaction), and the size and shape of the container it is piled into. Generally, the higher the moisture content of biomass, the higher the bulk density due to void spaces being filled with water (that is more dense than biomass).

Table 2.1 illustrates some of the major differences between biomass substances. Deinking mill sludges typically have very high ash content due to the inks and fillers (clay, kaolin) found in recycled material. This ash content has a direct effect on the calorific value of the sludge, making it less desirable for combustion and subsequent ash handling. The other sludges show similar characteristics to those of bark with equal to slightly higher dry HHV values. It should be noted that the solids content of the sludges is significantly lower than that of the bark, which means that the actual heating values for sludge will be lower than bark because of the excess water present in the sludge. 50% dryness is on the low end for bark, and can reach 80% in dry summer conditions. Sludges will range from 20% to about 40% dryness using conventional dewatering technology and depending (among other things) on the amount of biological sludge contained in the mixture. The ash content for bark and sludge is similar, and bark has been burned in mill power boilers for a long time, which indicates that sludge is a viable energy source (Scott, 1995).

2.3 – Sludge Disposal Techniques

Biomass disposal methods can be broadly categorized into beneficial and non-beneficial (Girovich, 1996). Non-beneficial options include disposal into landfills or monofills, incineration (not to be confused with combustion) and ocean dumping. Disposal options for which some benefits are realized include: land application (agricultural and otherwise), use as landfill cover, composting, animal bed lining, and thermal treatment for energy recovery. Two of the most commonly used disposal techniques are combustion of dewatered waste (sludge) for steam production in a mill power boiler, and landfilling. Generally, mills are landfilling less and landspreading and composting more. The advantages and disadvantages of combustion are discussed in Section 2.4. The following sections will further explain some of the waste disposal options that are currently being exploited.

2.3.1 Landfilling

Landfilling has been the historical method of choice for biomass disposal, and remains the primary disposal technique for many mills (Scott, 1995; NCASI, 1999; Hackett et al., 1999). The landfilling option is increasingly less favourable given that the same dewatering steps are required, but no benefit is derived from the waste. In addition, there is the cost of transporting the sludge as well as the increasing environmental restrictions placed on disposal sites. Landfills must now be constructed with leachate collection systems and a plan for closing out the site and monitoring it into the future. The current trends show that mills are moving away from this disposal technique and looking to increase combustion and other beneficial options.

2.3.2 Incineration

Incineration is not often considered as an option for pulp and paper mill sludge management since the purpose of incineration is to simply to reduce the volume of the sludge to facilitate landfilling without capturing the energy contained within the biomass. Incineration is typically reserved for municipal sludges that are contaminated with pathogens that need to be neutralized prior to landfilling.

2.3.3 Landspreading

Landspreading involves spreading sludge on either forest or agricultural land (Scott, 1995). This disposal technique is beneficial since the carbon, as well as nutrients (nitrogen and phosphorus), that remain from the water treatment process can improve soil for agricultural purposes.

The disadvantages of landspreading include investment in equipment (for transport, storage and spreading) and the fact that the sludge must be fully characterized to be deemed acceptable and safe for the environment (Saabye, 1997). Issues such as heavy metals, pathogens and odour are central to the land application program working. Typically, a mill has farms and forested lands located nearby. The ideal situation is to pump the sludge in its liquid form (thus eliminating transport costs) and spray it on the receiving area, but this is rarely the case, so dewatering of the sludge is still required to facilitate transport.

The economics of land application are varied due to differences in each mill's particular scenario. For example, transportation costs can be anywhere from $3 - $12 per tonne, and the cost of application / incorporation can range from $7 to $15 per tonne of dewatered sludge. Additional costs can be incurred for storage facilities and site preparation including fencing, drainage and road access (Forste, 1996). Although this is potentially a more viable option than landfilling, it is clear that there are still costs involved for the mill. In addition, the long-term environmental effects need to be monitored, particularly if the sludge is used for agricultural purposes.

2.3.4 Microbial Degradation

Composting:

Composting occurs when microorganisms decompose organic matter, releasing CO_2, water and heat. When the biological reaction is engineered to produce a desired effect, the process is known as composting technology.

Composting seeks to achieve the following:

- to create decomposed organic material suitable for sale as a soil amendment
- to reduce the volume of the initial material
- to destroy pathogens present in the initial material through the high (>60°C) and sustained temperature found within a properly operated system
- to remove moisture

In recent years, some mills have begun using this sludge disposal option as an alternative to landfilling and landspreading. Advantages include the creation of a useful product and reduction in sludge volume (important if landfilled). The disadvantage of composting is that the treatment costs are higher than for simple landfilling. Advanced systems require infrastructure such as enclosed buildings, aeration equipment, material handling and control systems.

Anaerobic Digestion:

Composting in the absence of oxygen can be termed as anaerobic digestion. The products of anaerobic digestion are methane (CH_4), carbon dioxide (CO_2), ammonia (NH_3), hydrogen sulphide (H_2S), and water. The gases produced can be captured and burned similarly to natural gas. The drawbacks of anaerobic digestion are the complex infrastructure such as gas tight reactors, gas captation and conversion systems (McKendry, 2002).

2.3.5 Other Beneficial Uses

A variety of other beneficial sludge disposal options are available to a waste treatment plant operator. It is important for each mill to assess its situation and determine which options are most advantageous on an economical, technological, and environmental basis. These alternative beneficial options are briefly described below.

Recover to Process:

Depending on the quality of the sludge, it can be returned to process to be integrated into product as filler material (Scott, 1995). The types of product that it can be incorporated into are limited to heavy grade packaging and construction materials. Typically this applies only to primary sludges that consist mostly of fibre and fillers.

Animal Feed/Bedding:

This disposal option requires some form of compaction or increased dewatering (centrifuge, pelletization, dryers) to dry the sludge to a level appropriate for use as a food source or even an absorbent, e.g. animal bed lining and cat litter. Studies have shown that certain types of sludge contain sufficient protein and nutrient concentration to justify use as a low quality animal feed (Wiegand, 1994), however, this is not a broadly applied solution.

Other Thermal Treatments:

In addition to the direct combustion of biomass, other thermal processes are available to reclaim the calorific value. Figure 2.2 shows an overall flowchart of the possible routes involved in biomass transformation.

Gasification involves burning biomass at high temperatures with restricted air flow which leads to incomplete combustion in the inert material of a fluidized bed. This partial oxidation leads to gas products like carbon monoxide and methane that can then be reburned to release energy. Pyrolysis involves heating biomass in the complete absence of oxygen to convert the biomass to useful products. This process can be used to produce charcoal, bio-oils and fuel gases. Liquefaction and hydro-thermal upgrading (HTU) are still at the pilot scale. The thermal depolymerization process (TDP) is also new on the market and makes use of flash evaporation of the water followed by distillation steps to eventually create light fuel oil out of almost any carbon-based material (Lemley, 2003).

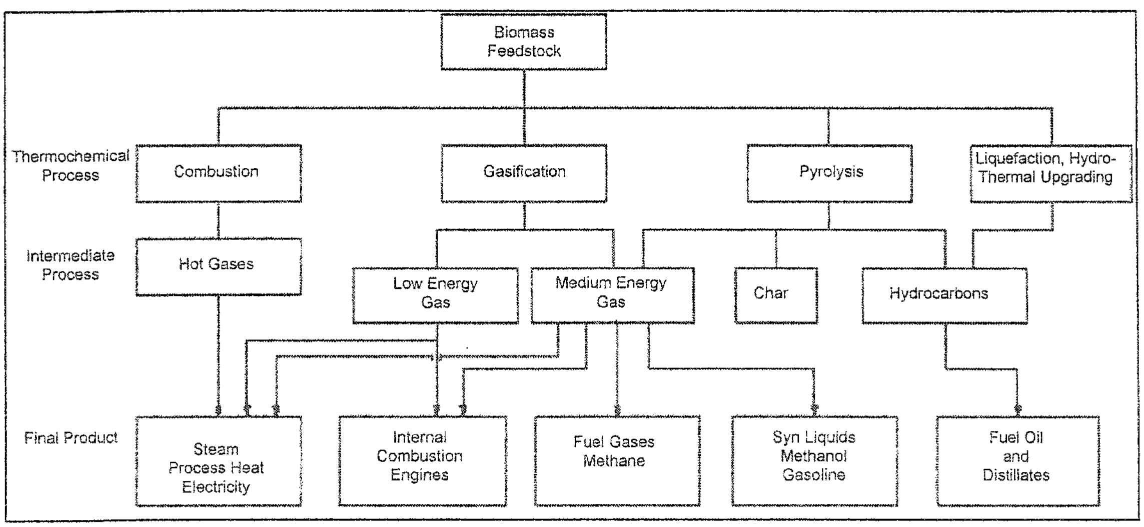

Figure 2.2: Biomass Treatment Flowchart (McKendry, 2002)

Where sufficient capacity exists, a chemical mill can also dispose of its biological sludge directly in the black liquor evaporators. This uses technology already in-place and will produce some energy for steam. However, this option would cease to be useful if the mill were to increase production and therefore need its evaporators to be dedicated to black liquor treatment.

Landfill Cover:

Studies have shown that dewatered sludge can be used as a barrier for water infiltration into a closed landfill cell (Malmstead et al., 1999). The sludge would be used as one layer of the capping process and has shown to be effective at controlling moisture flow rates into landfill cells.

2.3.6 Trends in Pulp and Paper Industry Management of Residuals

Tables 2.2 and 2.3 show waste treatment sludge disposal options and the percentage of mills that use them.

Table 2.2: Paper Sludge Disposal Method Trends in the United States

Disposal Method	1979	1988	1995
	(NCASI, 1992)	(NCASI, 1992)	(NCASI, 1999)
Landfilling	87%	70%	51%
Combustion	10%	21%	26%
Landspread	2%	8%	12%
Recycle to Process	<1%	1%	6%
Other Beneficial	<1%	0%	5%

Table 2.2 indicates a decrease in landfilling and increases in other sludge disposal options. These numbers represent the disposal practices for wastewater treatment residuals only, and do not include other solid waste streams generated by the mills (woodwaste, inorganics, ash).

In Table 2.3, disposal methods for various solid wastes are presented for the Canadian, Quebec and U.S. pulp and paper mills.

Table 2.3: Paper Sludge Disposal Methods for the United States, Canada and Québec

Disposal Method	Sludges	Wood Residues	Inorganic Residues	Miscellaneous Residues
	CANADA (Reid, 1998)			
Landfilling	53%	19%	97%	77%
Combustion	38%	79.6%	0%	14%
Landspreading	5%	0%	3%	0%
Recycling	0%	0.9%	0%	9%
Other Beneficial	4%	0.5%	0%	0%
	Québec (AIFQ, 2000)			
Landfilling	38%	16%	92%	89%
Combustion	29%	79%	0%	4%
Landspreading	22%	0.6%	6.4%	1.1%
Recycling	1.2%	4.2%	0%	5.8%
Composting	9.3%	0.4%	1.5%	0.5%
	UNITED STATES (NCASI, 1999)			
Landfilling	51%	N/A	72%	63%
Combustion	26%	N/A	0%	6%
Landspread	12%	N/A	11%	3%
Recycle	5.5%	N/A	0%	0%
Other Beneficial	5.5%	N/A	17%	28%

Similar practices can be seen in both countries particularly with respect to sludges. Québec stands out in that a larger percentage (22%) of its sludge is sent for landspreading, indicating that this region is more accepting of alternative disposal techniques (AIFQ, 2000). Woodwaste has traditionally been combusted in the mill's power boilers, but as landfilling loses favour, more and more mills are starting to mix wastewater sludge with the bark to be combusted (Kraft and Orender, 1993).

2.4 – Sludge and Biomass Combustion

Combustion, or thermal treatment, is a sludge disposal option being increasingly used for several reasons. First and foremost, if the solids content is high enough, combustion recovers energy from the waste material that can be used to produce steam for the plant (Scott, 1995). In addition, the volume of the sludge is reduced substantially, leaving only ash to be sent to landfill or possibly for beneficial end use (integration into cement or roadways for example).

Often mills maintain the facilities necessary for sludge combustion as part of their normal operations, and thus do not rely on negotiations with third parties, which is the case with external landfills and landspreading. Combustion is differentiated from incineration in that the goal is to recover energy, while the goal of incineration is to reduce the volume for landfilling and to destroy pathogens.

Sludge has been described as "difficult to burn" (Kraft and Orender, 1993) mainly due to its high moisture content, low oxygen content and occasionally high ash content. Sludge dewatering typically can only bring the sludge up to a solids content of 30 to 40% (NCASI, 1992), with the upper range being more and more difficult to achieve with increasing concentrations of secondary sludge. However, boiler efficiency drops significantly when the material being burned has a moisture content greater than 45-50% (Kraft and Orender, 1993). Liang et al. (1996) have demonstrated that boiler efficiency and moisture content are inversely related to one another (see Figure 2.3). Boilers are required to deal with the excess moisture found in wet biomass, which leads to larger volumes of flue gas being produced. This results in more elaborate air handling systems downstream of the boiler. Sludge has less fuel-bound oxygen than does woodwaste (see Table 2.1), and thus requires more combustion air to achieve the same combustion zone temperatures. Ash content is also variable in different sludges. Higher ash concentrations can lead to problems of reduced combustion temperatures and increased flue gas volumes (Kraft and Orender, 1993).

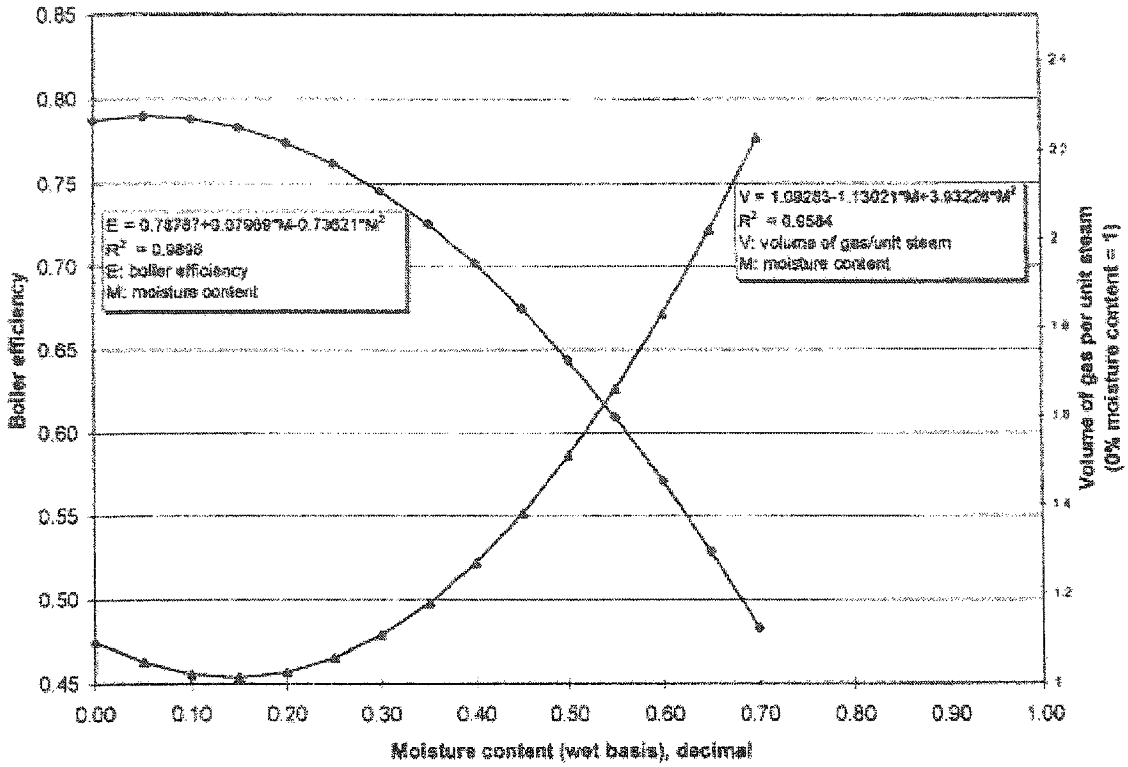

Figure 2.3: Boiler Efficiency and Effluent Gas Volume as a Function of the Moisture Content of Fuel (Liang et al., 1996)

To maintain proper combustion zone temperatures in a boiler, a balance must be kept between the fuel moisture content, ash content, and bound oxygen. The fact that little can be done for the two latter components dictates that the best opportunity for the operator to increase efficiency is to lower the moisture content of the feed material.

For these reasons, it is often not appropriate for mills to burn sludge directly after dewatering, requiring that steps be taken to increase the solids content. This can be accomplished by mixing the sludge with a drier substance, such as the woodwaste (bark) mentioned earlier. This practice is common in industry because of the abundance of waste material as well as the relative simplicity of the process. The other option is to pre-dry the sludge in order to remove excess moisture. This concept will be developed further in Section 3.

2.4.1 Combustion Techniques

Mixed primary/biological sludge has been included as fuel in the combustion process for some time at pulp and paper mills, however the quantity and moisture content of material being used has been changing recently. If current trends persist, the practice of sludge combustion will continue to increase while the required dryness will become more and more difficult to achieve given the higher percentages of biological sludge present in mixed dewatered sludge. Mill sludges can be very good fuels, possessing calorific values that are about 75% of bituminous coal (on a dry basis) with similar to lower ash content. The advantages of burning sludge and woodwaste include the following:

- it is an inexpensive fuel
- it displaces fossil fuels (reclaimed energy reduces or eliminates fossil fuels used for steam production)
- it reduces or eliminates sludge landfilling (or other disposal techniques)
- biomass burning does not contribute to greenhouse gas emissions (see Section 2.4.2)

The disadvantages of using this fuel source include the following:

- its high moisture content can reduce combustion flame temperatures resulting in:
  - incomplete burning (CO production, reduced steam production, etc)
  - supplemental fuel required to maintain combustion
- its higher ash content results in waste ash that must be managed
- increased flue gas is produced from the excess air used to supplement for lower fuel-bound oxygen
- sludges high in silica and sodium salts could have low melting point ashes resulting in the formation of slag (Brunner, 1992)

Most mills have access to some form of waste boiler (hog fuel/power boiler, biomass burner, etc.). The implementation of a biodrying system will typically use existing biomass burning technology because of the high capital costs associated with installing or retrofitting boiler equipment. Examples of typical mill equipment that can be used for biomass burning are given below.

Stoker Furnace:

The stoker furnace is a classic combustion method used by many mills to burn materials such as woodwaste and coal. There are several configurations (see Figure 2.4), but in general, the fuel is fed onto a metal grate where combustion takes place. Smaller fuel particles ignite in suspension and are burnt in mid-air, while heavier particles fall down to the grate and burn there. The grate configurations are variable, having arrangements where the grate is static, inclined, or moving. Typically the material is conveyed (by an incline or by a moving/vibrating grate) towards the feed side of the reactor. This transports the ash for removal from the bottom of the unit. For sludge particles to ignite, they must reach an auto-ignition temperature by absorbing heat from the air in the reactor chamber, primarily by radiation (Kraft, 1991).

If wet sludge reduces the combustion zone temperature, then the combustion air temperature must be increased to compensate. As an example, the air must be 10°C higher to make up for every 1% lower sludge dryness (Kraft, 1993). Sometimes, to prolong combustion equipment life, the grate is water cooled to allow for hotter air to be injected. Since this traveling grate technology is sensitive to moisture content, it is limited to either drier sludges or to reduced feed rates. The process is also slow to respond to changes in the inlet sludge moisture conditions making it sensitive and more difficult to control.

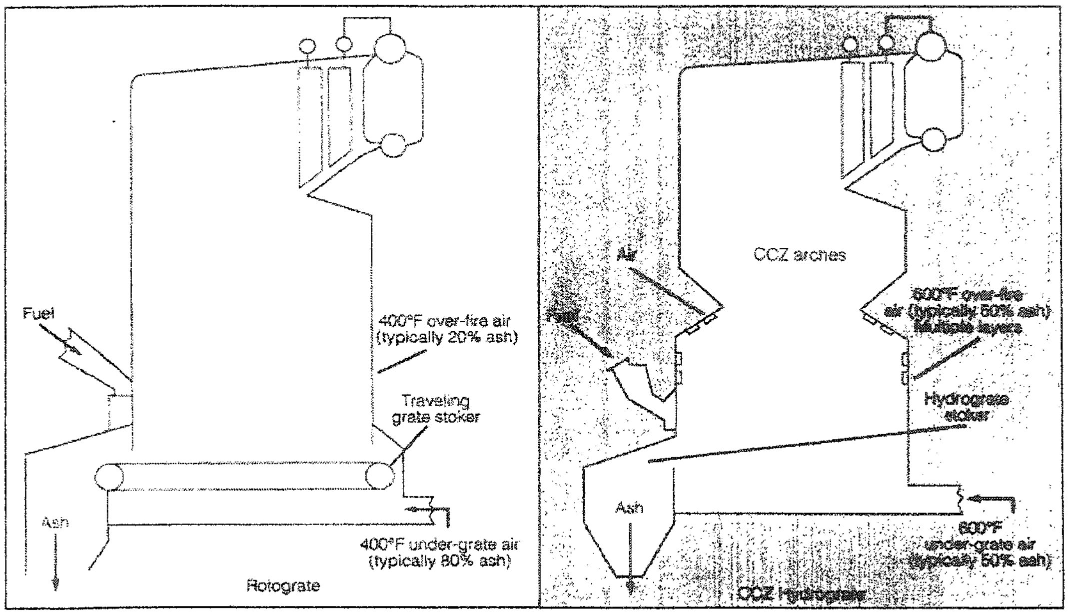

Figure 2.4: Stoker Type Furnaces (Kraft, 1991)

Fluidized Bed:

This fluidized bed reactor is basically a conventional power boiler that has a bubbling bed of inert material that is fluidized by combustion air forced up from below. This is an improvement over the grate stoker type of reactor because the fuel particles are completely surrounded by heat and air (Kraft, 1991). The ash is blown upward and out through the top of the reactor. Fuel can be fed onto the inert layer or directly into it, depending on the way the system is operated. The sludge particles absorb heat from the bed material immediately and ignite. Figure 2.5 shows a simple sketch of a fluidized bed furnace. Fluidized beds typically operate between 760°C and 900°C, lower than normal boiler temperatures because of the increased heat transfer of the inert material to the fuel particles. Because of this, wetter sludge (38% - 42%) can be sent to the fluidized bed furnace (Scott, 1995). Due to the high heat capacity of the inert material, the system is better equipped to deal with changes in the feed moisture. Some of the disadvantages of fluidized bed technology include more complex monitoring and system control as well as bed fouling. The presence of salts could form slag resulting in clogged bed material. Sludge characteristics need to be carefully evaluated before proceeding with this type of operation. A circulating fluid bed eliminates excess heat by removing some of the inert material, cooling it and reintroducing it to the bed. Another method is to create a bubbling bed gasifier that uses less combustion air, resulting in uncombusted gases that leave the reactor to be burned in the furnace. In-bed heat exchangers can also be used to control bed temperature and ensure fluidization. The inert bed material must be kept in the ideal operating temperature range (typically 1400°F to 1600°F). This temperature is affected by the quality of the fuel being combusted. If the calorific value of the feed is not sufficient to keep the temperature in this range, then supplemental fuel must be added to increase it. The reverse is also true; if too much heat is generated in the bed, it must be cooled by the methods mentioned earlier. Certain pulp sludges release heat equal to the energy needed to evaporate the water and to raise the particles to their ignition temperature. This typically occurs in the range of 38% to 42% solids for the feed material (Kraft and Orender, 1993).

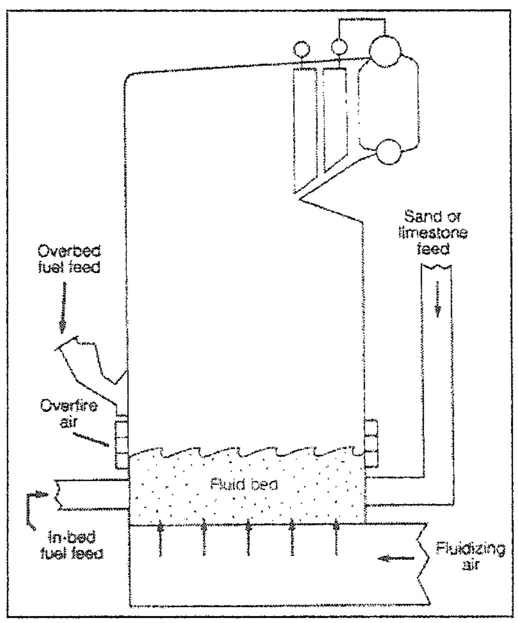

Figure 2.5: Fluidized Bed Furnace (Kraft, 1991)

2.4.2 Air Pollution Control, Biomass and the Kyoto Protocol

Boiler operation with biomass is different compared to fossil fuels. For example, there is more particulate matter generated when burning bark than with natural gas. When a power boiler combusts increased amounts of biomass, the air pollution control equipment must be monitored to ensure that it can handle the increased load. Electrostatic precipitators and cyclones can typically deal with these increased particulate loadings. High moisture, low oxygen and higher ash contents in the biomass feed can affect the combustion process and lead to incomplete reactions. It has been found that when increased amounts of sludge are burned along with bark, there is an increase in sulfur, nitrogen and particulate emissions (Kraft and Orender, 1993). Hence, more volatile organic compounds (VOC's) as well as SO_x and NO_x are generated.

The practice of biomass combustion will certainly benefit from the changes proposed in the Kyoto Protocol, which aims to reduce the emission of greenhouse gases (GHG's) that have been implicated in global warming and climate change. The impact on the atmosphere of releasing industrial gases is assessed by expressing the various components in terms of carbon dioxide equivalents (CO_{2E}), since CO_2 is the gas released in the largest quantity. For instance, methane (CH_4) has a greenhouse gas potential 21 times more harmful than CO_2 (Galle, 2001). Therefore, 1 tonne of methane released to the atmosphere (from landfill gas for example) would be quantified as 21 tonnes of CO_{2E}. The primary goal of the Kyoto Protocol is to reduce, by 2008-2012 (for Canada), the quantity of GHG released to the environment to 6% below the 1990 level of 607 million tonnes of CO_{2E}, and to maintain this level over the period 2008-2012 (Browne, 2003).

The carbon dioxide produced through the combustion of biomass is regarded differently from that of fossil fuels. It is assumed that the carbon sequestered within the biomass would have been returned to the environment through decomposition during its natural lifecycle. Since the cycling of biomass occurs on a comparatively short timescale compared to fossil fuels, the CO_2 released from biomass burning is not counted in the overall emissions of a particular combustion system. Combustion of biomass is therefore considered to be "net-zero" with regard to CO_2 release. A mill that is burning fossil fuels can significantly reduce its GHG emissions by replacing existing oil or gas fired boilers with ones that are biomass fired.

Although the implementation of the Kyoto protocol is still uncertain with respect to timelines and penalties/compensation for compliance, the industry is being proactive by starting to deal with the problem immediately. Canada is considering a permitting system where the government would dispense free permits for 85% of a mill's GHG emissions, leaving the mill to purchase the remaining 15% (Browne, 2003). The economic benefits that a mill could potentially reap from this are two-fold. First, the mill would benefit from the use of a fuel source that is far less expensive than fossil fuel. Secondly, the CO_2 that they are displacing from reduced fossil fuel combustion could exceed the amount that they are permitted to release. Any excess could be sold on the open market as "CO_2 credits". The value associated with these credits is not yet established, but preliminary values have been between $10 and $50 per tonne of CO_{2E} (Browne, 2003).

2.5 – Summary of Sludge Disposal Techniques

As with any complex problem, a variety of solutions exist for sludge management. Table 2.4 provides a synopsis of the pros and cons of the methods, which have been presented in this section.

Table 2.4: Advantages and Disadvantages of Sludge Disposal Techniques

Disposal Technique	Advantages	Disadvantages
Combustion	-Energy reclaimed from waste -Eliminates sludge disposal (volume reduction) -Displaces fossil fuels	-Capital costs of combustion technologies and their upkeep -Air pollution challenges -Ash management -Equipment corrosion
Landfilling	-Established -Simple disposal, no treatment, just transport	-Transport offsite -Environmental concerns -Increasing costs -Methane production (GHG)
Landspreading	-Improves soil characteristics -Returns some nutrients & carbon to environment	-Potential liabilities (metals, pathogens, etc.) -Odour -Transport & spreading equipment -Characterization and permitting requirements
Composting	-Produces saleable product -Destroys pathogens and reduces volume of sludge -Low energy consumption	-Capital costs associated with facilities for composting -Sufficient market for product/transport -Time required for treatment -Typically batch operation
Anaerobic Digestion	-Volume reduction -Produces saleable biogas -Improved properties of digested sludge	-Capital costs -Digested sludge disposal remains a problem
Recycle to Process	-Reclaims value in new products -Reduces burden on other sludge disposal techniques	-Can reduce product quality -Limited to specific paper products -Sludge pre-processing required
Thermal Processes	-Energy is derived from sludge -Potential for profitable operation -Sludge is kept onsite	-Complex, unproven systems -High capital cost

When considering which option(s) are best suited to a mill's waste sludge situation, four main factors; cost, technical feasibility, potential liability, and available markets must be weighed against the mill location and type, sludge characteristics, as well as the corporate philosophy and local regulations (Wiegand, 1994).

Landfilling is clearly a non-beneficial disposal option, yet it remains the most used technique in the industry, illustrating that short-term costs are a primary concern for mills. There are systems that can deal with the sludge problem effectively and potentially at lower cost, however there are barriers to their application such as capital cost. This is especially true for newer technologies such as pyrolysis. Simple combustion offers fewer disadvantages primarily because:

- any mill that is considering sludge burning will typically have a woodwaste boiler onsite
- there is no external market for the energy, therefore the mill does not need to worry about finding "buyers" for its sludge (required for composting and landspreading for example)
- excess energy is increasingly being transformed into electricity
- the reliability and potential for substantial savings (fuel, reduced disposal costs) puts combustion ahead of many sludge disposal options

The background information provided in this section is applied to later in this thesis. An understanding of biomass characteristics is essential to the development and analysis of the laboratory experiments of Section 7, while disposal methods and combustion techniques serve as technical and economical consideration in the analysis performed in Section 8.

3.0 – BIOMASS DRYING TECHNOLOGIES

There are many competing technologies for sludge drying. Some key ones are reviewed in this section.

3.1 – Drying Techniques

The difference between drying and evaporation lies in the fact that evaporation occurs at water's boiling point while in drying, moisture is removed as vapour in air (Geankoplis, 1993). Moisture contained in the material to be dried can be classified as bound or unbound (Girovich, 1996). Unbound moisture is present on the surface of the particles and is removed at a constant drying rate. However, bound moisture is more difficult to remove since it is trapped inside the particles and must be transported by diffusion or capillary forces to the surface to be evaporated. Bound moisture is also contained within the cellular membranes of microorganisms and is challenging to extract once the unbound moisture has been removed and the rate of drying falls off. Other parameters also affect drying rates such as the amount of agitation and the heat capacities of the vessel and materials to be dried.

3.2 – Dryer Designs

The two main dryer types are direct and indirect units.

3.2.1 Direct Dryers

Direct drying systems remove moisture by stripping it away in the gas (in this case, air) phase. The principle mechanism for water removal is convection. The water and solids of the material being dried will achieve wet-bulb temperature and no higher (Girovich, 1996). Essentially, psychrometric relations control the rate of water removal in a convective operation.

The advantages of these types of systems are their relatively simple design and high throughput. The disadvantage of direct drying systems is that they require large quantities of hot air to dry material. This air must first be heated (or diverted from some other source, such as flue gas), passed through the dryer, and then expelled because it is laden with moisture making it ineffective for further drying. Without heat exchanger systems the energy used to heat the air is lost.

One of the most common designs for sludge drying is the rotary drum dryer (Wimmerstedt, 1999). The solids traverse the drying chamber due to the incline of the drum and internal flights that push the material as the drum turns. Typical feed temperatures are around 480°C for biosolids with exit temperatures in the 85° – 105°C range (Girovich, 1996). Sludge enters at a fairly dry (>50%-60%) solids content for handling reasons, so that it will not be sticky and will fall properly inside the drum. Sludge may have to be back-mixed with drier material to lower the overall inlet moisture content. Exit dryness values are typically >90% solids (Albertson, 1992).

Conveyor dryers use some form of belt or movable trays to move material through a heated chamber. This type of system requires feed material solids in the 20% to 25% range to ensure that air can move effectively through and around individual particles as they lay on the conveyor.

Fluid bed dryers are similar to the fluidized bed combustion systems discussed earlier, but without the inert bed material. Wet biomass (in granular form) is introduced into the reactor and is fluidized by an upward stream of hot air. Dried particles are carried out the top of the chamber through a rotary air lock and separated. This type of technology is best suited for drying very dry sludge (>50% solids) because wetter sludge will be too heavy and will not fluidize. The final product of this system is almost completely dry.

3.2.2 Indirect Dryers

The primary driving force for water removal in an indirect drying system is conduction. That is, the wet biomass is placed in contact with a heated surface and the energy is transferred from the surface to the particles, evaporating the water that is then removed by natural convection or helped along with a ventilation system (becoming a dual convection/conduction system). The heat transfer surface is what differentiates the various indirect dryers; some use hollow paddles or disks while others use flat shallow trays. Indirect drying systems are typically kept at a small vacuum to further increase the evaporative effects.

Disk and paddle indirect dryers have various configurations of hollow chambers for hot fluid circulation. Wet sludge is fed in at one end and is transported to the other end by slow rotation and the use of baffles and flights. The heat energy is transferred to the sludge, evaporating the water. One of the main disadvantages of these dryers is dealing with sticky sludges that can adhere to the surfaces, reducing the heat transfer efficiency. Scraping systems and material selection can help with this problem. These units are well suited to producing dry product in excess of 90% solids.

A variation on both the disk and paddle type of indirect drying systems are screw conveyor/presses that use indirect heat injected into the central shaft which is in turn radiated out to the screw flights. Many mills use steam injected screw presses in their dewatering train, helping to increase the overall dryness out of the screw press in excess of 40% solid material. Tray dryers are either static systems where the material sits on heated trays until it is dry or active ones where the material is shifted and scraped from one section to the other, gaining in dryness at each step.

Trays are heated with oil or steam and a vertical central shaft moves the material from tray to tray (material falls by gravity). This system produces a very dry product (>90% solids) but requires a fairly dry feed (55%-75%), and so some back-mixing of dried material is required (Girovich, 1996). The advantages of this system are the small footprint required and the high quality of pelletized product that is formed. Disadvantages include the height of the unit, the fact that only half the hot surface is used (top side of the trays, not the bottom) and the large overall mass of the system.

3.2.3 Commercialized Alternative Sludge Drying Technologies

The following technologies are entrepreneur-developed solutions designed to address issues related to pulp and paper mill sludge drying. They are either adapted from traditional technologies or in some cases offer unique treatment options. The theory behind these options is often sound, but the systems sometimes lack the market penetration and necessary experience to become viable.

Alternative Green Energy Systems (AGES):

This novel technology operates as a biomass-dust combustion system. Dust burners operate with a suspension of fine combustible particles to produce a flame similar to that of an oil burner. The system produces a flammable dust from woodwaste using a KDS (Kinetic Disintegration System) called the Micronizer with product solids typically >92% and a narrow particle size distribution (Burns, 2002). The Micronizer works to separate wood fiber and biosolids from water with disintegration and de-watering completed in a single step. This technology has its origins in the mining industry where it was developed for the disintegration of metal ores. The Micronizer was developed to process rocks at a fraction of the cost by creating resonant shock waves inside a chamber through the high-speed rotation of a rotor. The interaction of the shockwaves and the material inside the chamber generates internal stresses so great that the tensile strength of the material is exceeded and the particles literally blow apart. Figure 3.1 shows a schematic of this system. The system can process pulp and paper mill sludges as wet as 25% solids and produce dry powder greater than 85% solids content. This has been done at the pilot scale in the order of 1 to 1.5 tonnes per hour. The biomass dust that is formed is separated with a cyclone and sent to a dust burner to produce energy in the boiler. An advantage of dust burning is that there is less ash formed during the combustion process. Residual carbon in the ash is reduced resulting in less waste to deal with and greater energy reclamation. What remains is purely inorganic ash that has a potential resale value as filler material (in concrete for example).

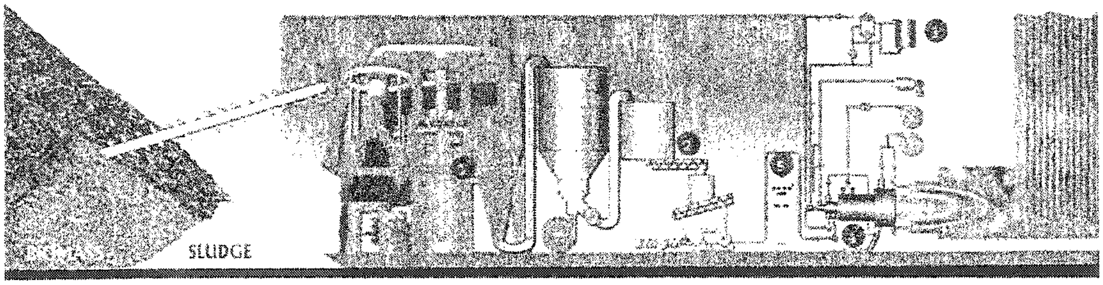

Figure 3.1: AGES Treatment System (Burns, 2002)

Plasma-Assisted Sludge Oxidation (PASO):

This relatively new drying technology developed by Hydro Quebec uses electrical power to oxidize sludges at relatively low temperatures (600°C). The system's basic configuration is a rotating refractory-lined drum that acts as a combustion chamber. Wet sludge is fed by a screw conveyor into the front end of the drum. The material is dried and oxidized in the rotating drum with the help of an electric plasma arc torch located at the far end of the combustion chamber. The torch maintains optimum oxidation reactions and compensates for losses caused by excess moisture in the feed material. Figure 3.2 depicts the simplified process schematic. Ash collects at the bottom of the rotating cylinder and in turn acts as a heat transfer medium between the walls and the wet sludge. Excess ash is removed from the far end of the reactor. The system produces a dry ash that reduces the overall volume of the incoming sludge by 95%. Power consumption is estimated at 105 kWhr/tonne wet sludge treated. At this time the PASO system is at the pilot scale. About 4 dry tonnes per day can be treated with existing system configurations. Multiple units would need to be used to meet the sludge handling needs of a large wastewater treatment plant (Bacon, 2001).

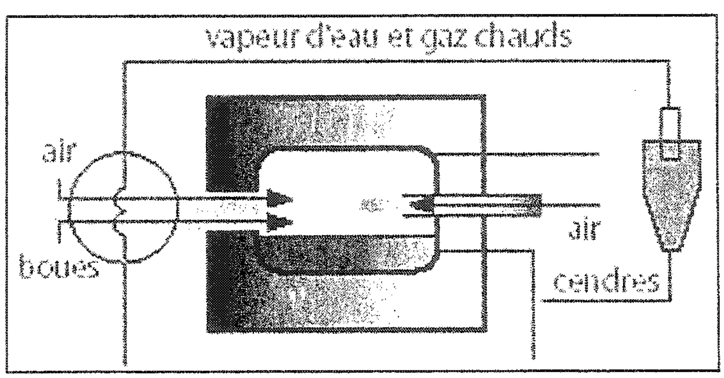

Figure 3.2: Plasma Assisted Sludge Oxidation (Hydro-Québec, 2003)

Mabarex Dry-Rex:

Another new technology is the Dry-Rex system, which uses large quantities of low pressure, low temperature air to dry sludge at ambient conditions (10°-30°C). Dewatered sludge is fed into an extrusion process that forms spaghetti-like sludge fragments (1-5 mm in diameter, 5 – 10 cm long) that then fall onto a conveyor system. Air is blown through and over the sludge on the conveyor, stripping moisture by convection. The top conveyor belt feeds the one beneath it and the sludge becomes drier as it cascades down through the process. Each level has its own ductwork that adds fresh air and removes saturated air. Recycling portions of the air helps to reduce the energy requirements (primarily due to blowers) of the system. Figure 3.3 shows this process.

The advantage of Dry-Rex is that it uses ambient air and does not require pre-heating (although this improves moisture removal). Disadvantages include the reliability of the extrusion process, operation in cold climates and variable humidities, treatment of large amounts of waste air and the fact that, without increased temperatures, the diffusion of bound moisture from within sludge particles is minimal, promoted only by the removal of unbound moisture (Barré, 1999).

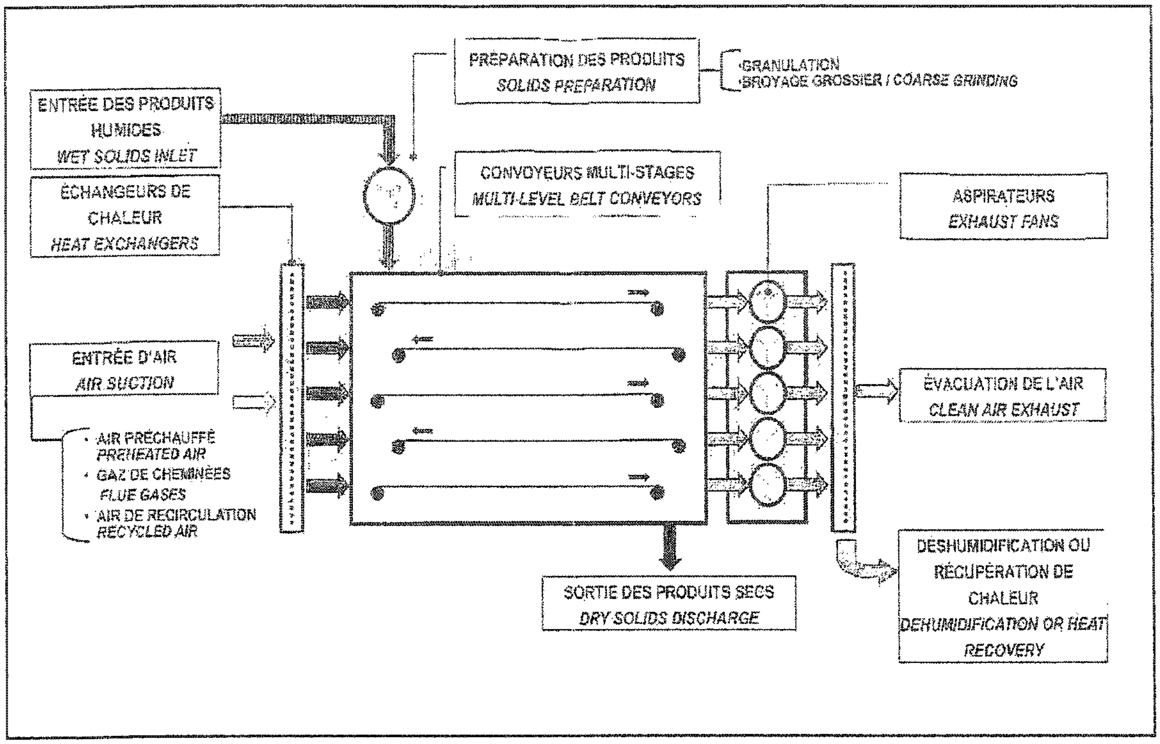

Figure 3.3: Mabarex Dry-Rex Biomass Drying Technology

Carver-Greenfield (CG) Process:

The CG process uses multi-effect evaporators, similar to those used for the concentration of liquor, to dry liquid biosolids (Albertson, 1992; Girovich, 1996). The biosolids are mixed with a fluidizing carrier oil which allows for their transport through the various unit operations (evaporators, separators). The advantage of this system over single stage evaporators (such as flash, steam tube or spray dryers) is that waste heat is used to pre-heat each stage, ensuring that energy use is maximized. Steam energy is used only at the last stage to evaporate the oil, leaving only the dry solids. Solids content is typically greater than 90% with little (0.2–0.5%) oil retention. Most of the oil is retained in the CG process and the waste oil (containing particulate biomass) can be combusted in a furnace. Azarniouch (1995) described how the CG process could be used to create a dry product that can be combusted to destroy the chlorinated organic compounds typically found in sludge from a bleached kraft pulp mill (See Figure 3.4). The disadvantage is that this is a very complex and capital-intensive system that requires high levels of maintenance and control.

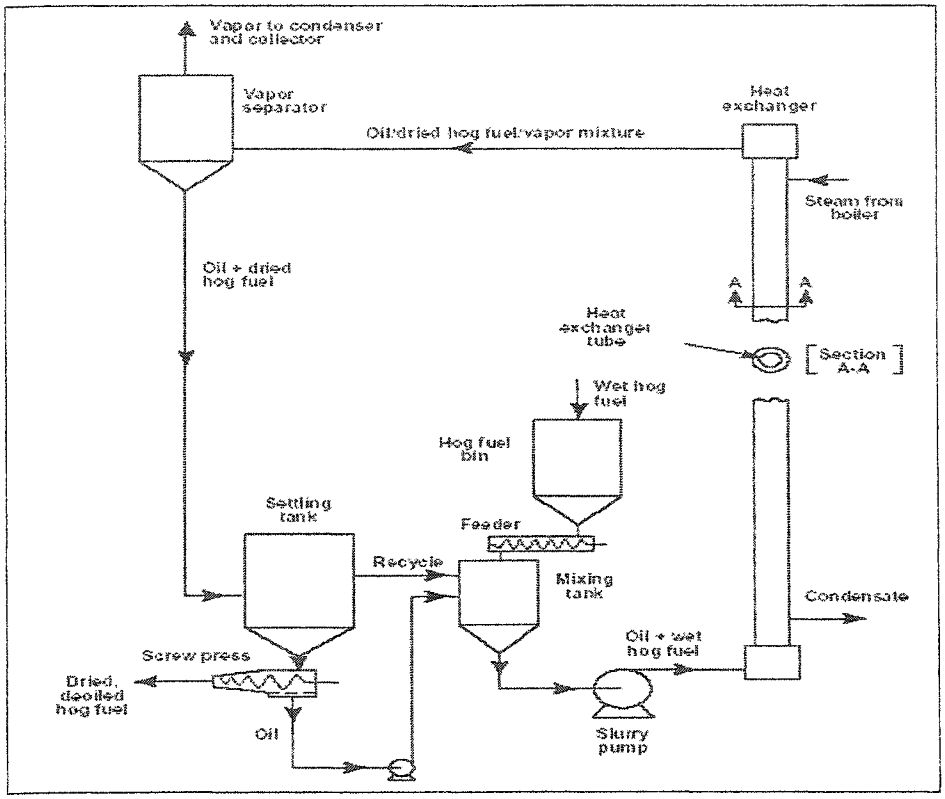

Figure 3.4: Carver-Greenfield (CG) Pilot Process (Azarniouch ,1995)

3.3 – Performance Indices for Sludge Drying Technologies

A comparison of drying processes requires an understanding of their separate benefits and drawbacks, their applicability to dry a given material, as well as specific performance ratings. Table 3.1 compares the different technologies discussed in this section in terms of the energy required to remove given quantities of water.

Table 3.1: Sludge Drying Technical Comparison for One Tonne of Wet Material

A	B	C	D	E
Drying Technology	**Specific Thermal Rate** (kJ / kg H_2O)	**Product Dryness Change** (% solids) (xx% → xx%)=range	**Water Removed** (kg) ["C" x 1000 kg]	**Energy Consumption** (GJ/ wet tonne) ["B" x "D"/10^6]
Direct Dryers				
Rotary	3,600 – 9,200[1,2]	40% (~55%[3] → ~95%)[1]	400	1.44 – 2.51
Conveyor	5,500– 6,000[2]	70% (~25% → ~95%)[1]	700	3.85 – 4.20
Fluid Bed	4,000 – 6,000[2]	50% (~50%[3] → ~100%)[1]	500	2.00 – 3.00
Indirect Dryers				
Disk	2,510 – 2,930[1,4]	70% (~25% → ~95%)[1]	700	1.76 – 2.05
Paddle	2,721 – 2,847[1]	25% (~25% → ~50%)[1]	250	0.68 – 0.71
Multi-Tray	2,680 – 2,805[1]	30% (~65% → ~95%)[1]	300	0.80 – 0.84
Alternate Drying Systems				
AGES	317 – 793[5,6]	40% (~50% → ~90%)[5]	400	0.12 – 0.32
Plasma-Arc	~ 500[7,8]	75% (~25% → ~100%)[7]	750	0.38
Dry-Rex	180 - 540[9]	55% (~25% → ~80%)[9]	550	0.10 – 0.30
Carver-Greenfield	1,162[4] – 3,720[1]	80% (~20% → ~100%)[1]	800	0.93 – 3.00

1: Girovich, Chapter 6 (1995)
2: Mujumdar and Menon (1995)
3: Product is recycled to increase feed dryness
4: Albertson (1992)
5: Burns (2002)
6: 10 – 25 lbs. water removed per kWh
7: Bacon (2001)
8: 105 kWh / tonne of 25% wet sludge
9: Barré (1999)

In order to normalize each of the processes, calculations were performed to show the energy required to dewater one tonne of biomass material. Each of the technologies is capable of drying within certain limitations with respect to feed and product dryness. Some systems desiccate the material, removing all water, while others simply increase the dryness to levels appropriate for further treatment. The total energy required to remove given amounts of moisture is then summed. Table 3.1 shows that the most energy intensive unit operations are the traditional direct dryers. These operate primarily by convection and use large amounts of excess air that must be treated afterwards. The indirect dryers present lower energy requirements than the direct ones due to conduction and convection being used simultaneously in most cases. The advantage of indirect drying is that there is little airflow, which in turn reduces the amount of post-system air treatment related to odour and particulate handling. Essentially the exit stream consists almost entirely of water vapour. While the reduced air pollution treatment requirement is a distinct advantage, indirect dryers are less efficient than direct dryers on a specific performance basis because the contact with the solid particles is less intimate. Furthermore, many pulp and paper mills already have extensive air handling systems that lend themselves well to direct drying systems. The alternate technologies show the lowest overall energy requirements for water removal, however they are not as prevalent on the industrial market and have shortcomings related to reliability, throughput and versatility. Table 3.2 summarizes some of the advantages and disadvantages of the drying processes discussed to this point.

Table 3.2: Advantages and Disadvantages of Sludge Drying Technologies

Drying Technology	**Advantages**	**Disadvantages**
Direct Dryers		
Rotary	-Numerous installations, good body of knowledge on their operation -Robust -Relatively low capital cost	-Heat losses in the exhaust -Large amounts of air to clean -Potential dust fires and explosions -High energy consumption -Low heat transfer coefficient[1]
Conveyor	- Numerous installations, good body of knowledge on their operation -Robust -Lower feed temperature requirements	-Large surface area needed -Feed must lay down uniform layer -Excessive waste exhaust air -Sticky sludge problematic -Only surface material exposed to air -Low heat transfer coefficient[1]
Fluid Bed	-Lower energy requirements -Uniform, very dry product -High heat transfer coefficient[1]	-Requires granular feed (pretreatment) -Poorly granulated product -Dust fires and explosions -Complex operation
Indirect Dryers		
Disk & Paddle	-Compact horizontal arrangement -Effective utilization of heating surface -Relatively energy efficient -Low air treatment costs	-Lumpy, dusty final product -Rotary equipment maintenance
Multi-Tray	-High heat transfer rates -Low power consumption -Low air treatment costs -Small footprint -High quality pelletized product	-Requires lots of vertical space -Bulky, expensive units -Only half the effective heating surface is used
Alternate Drying Systems		
AGES	-Low power requirements -Low capital and operating costs -Uniform product	-Paper mill would require several units to meet solid flows -Many unit operations -Not proven in the P&P industry
Plasma-Arc	-Sludge volume reduction -Low energy requirements -No fossil fuel needed	-Low throughput, multiple unit required with existing processing ability
Dry-Rex	-Low energy requirements -No fossil fuel needed -Ambient air used for drying	-System sensitive to inlet temperature and humidity -Massive amounts of exhaust air
Carver-Greenfield	-Efficient heat transfer rates -Dries difficult (very wet) substrates	-Very high capital cost -Complex system -Not generally applied in the P&P industry

1: Refers to volumetric heat transfer 100 – 300 [kcal/sec K m^3] for rotary & conveyor compared to 2000 – 6000 [kcal/sec K m^3] for fluid bed dryers. Mujumdar and Menon (1995)

Drying process selection is not simply a matter of comparing operating efficiencies. Price considerations, serviceability, compatibility with existing infrastructure and combinations of multiple drying solutions all factor into selection of the ideal drying process. Table 3.1 compares technologies based on their design limitations for acceptable feed and typical products dryness. These can alternately be used in order to save energy by producing material of lower dryness that could then be combusted. For example a rotary dryer could be used to pre-dry material for combustion rather than producing a 95% dry material. Technology combination is sometimes possible, however this will not be examined in this work.

In general, direct drying processes are heavy energy consumers and are only viable if waste heat sources (such as flue gas) are available, in addition to the air pollution control systems thereafter. Indirect dryers also require large energy inputs, typically in the form of superheated steam or oils. They are often limited by the amount of material that they can dry, particularly in a large waste producing industry like pulp and paper. Alternate drying technologies each try to address the disadvantages of traditional methods and are generally limited by their industrial application experience.

4.0 – DRYING IN POROUS MEDIA

When drying porous media, the material is static (no agitation) and the void spacing affects moisture removal. Convective mass transfer occurs when an air stream passes over exposed films of water located on surfaces within the porous media. If adequate porosity is present, convection is actually optimized due to higher specific areas (surface area per unit volume) compared to flow over a flat plate, for example. Conductive moisture removal (with indirect dryers for instance) occurs when heat is transferred to the solids being dried and when both liquid water and moisture vapour are transported in the voids by diffusion and capillary flow.

4.1 – Biopile Technology

Fundamentally, biopiles function on the principal that natural microbial populations within a soil matrix will, given the proper conditions, consume organic matter. Biopiles include backyard composting bins, bioventilation for hydrocarbon decomposition, and large scale biopiles for odour removal (Haug, 1993; Fahnestock, 1998). The most common biopile technology, however, is the composting process. Haug (1993) defines composting as, "*the biological decomposition and stabilization of organic substrates, under conditions that allow development of thermophilic temperatures as a result of biologically produced heat, to produce a final product that is stable, free of pathogens and plant seeds, and can be beneficially applied to land*".

This process becomes a technology when the conditions are engineered. This technology has been used to manage soil, residues, sediments and other porous media decontamination projects. A few examples of biopiles are presented here.

4.1.1 Examples of Biopile Processes

Bioventilation:

Bioventilation refers to biopile technology used to treat soil that has become contaminated with hydrocarbons (Fahnestock, 1998). The aerobic microbial activity is maintained through the proper control of moisture, oxygen and nutrients, and as a result, the petroleum products are consumed as a microbial food source. Bioventilation can be simple solution to a complex problem that cost-effectively eliminates toxic contaminants from large volumes of soil. These biopiles are limited by the length of time required for treatment (3 to 6 months), by excessive hydrocarbon loadings (> 50,000 mg hydrocarbon/kg), as well as their ability to degrade complex molecules such as polycyclic aromatic hydrocarbons (PAHs).

Biofiltration operates similarly to bioventilation, but treats a waste gas stream with a solid medium. Organic compounds in a gas outlet (odourous compounds, volatile organic compounds, hydrocarbons) are passed through a specialized matrix of soil or peat, amendments, and microorganisms in order for them to consume the contaminants. Biofiltration is typically employed as a polishing step following other air pollution treatment processes.

Biogas Extraction:

In the United States alone, 190 million tonnes of municipal solid waste (MSW) was disposed of in landfill sites during the year 1990 (Klass, 1998). Landfill cells act like large anaerobic biopiles, with microorganisms consuming the organic fraction of the MSW and converting it into CO_2 and CH_4, both greenhouse gases. This MSW contains biodegradable material varying from 30% to 60% by mass (Wilson, 1977). This number increases when wastes from the pulp and paper industry are disposed of, due to high biomass content (sludge, bark, etc…), and depending on the quantity of ash. While the degradation process will occur regardless of human intervention, these landfill sites can be controlled so as to extract the biogas and use it beneficially for energy production. This can be accomplished passively by inserting perforated pipes into the mass and allowing the biopile internal pressure to push gas out, or it can be extracted with pumps.

Composting:

As mentioned earlier, composting is the most widely recognized biopile technology. These systems come in a wide variety of designs and configurations and an explanation of them all is beyond the scope of this work. Haug (1993) gives an extensive list of technologies that are in operation today. In summary, there are two main categories of composting systems: non-reactor or open systems, and reactor or in-vessel systems.

The open systems include both agitated solid bed (such as windrow or "turned" composting) and static pile operations. Both of these can be operated under passive or forced aeration regimes. These systems are typically run as batch processes.

Enclosed reactor-type composting systems are continuously operating facilities that treat biomass like an assembly line. These systems can be subdivided into vertically and horizontally flowing units. In vertical systems, material is fed to the top of the composter and it cascades slowly down to be removed from the bottom, decomposing for the duration of its residence time. Horizontal reactors move the composting material from one end to another using either tumbling (rotary drums), agitation (screws, baffles) or conveyors.

4.2 – Flow Through Porous Media

The term porous media is defined as any material that consists of a solid matrix of particles with an interconnected void (Nield, 1998). This interconnected void allows for the flow of fluids from one end of the material to the other. The pore spaces in natural materials such as bark, wood, and sludge are non-uniform, unlike those of packed columns filled with glass beads for, instance. Despite the irregularities in the porosity of biomass, when a large volume is taken into consideration, averages can be taken over the entire space that allow for theoretical calculations to be made.

4.2.1 Porosity

We can characterize a porous medium first and foremost by its porosity (n) that is defined as the total volume of pores over the total matrix volume.

$$\text{porosity} = n = \frac{Pore\ Volume}{Total\ Volume} \qquad (4.1)$$

Therefore, the porosity of any given substance will vary between 0 and 1. Natural materials rarely exceed 0.6, but packing density (compaction) factors into the overall porosity. A distinction must be made between the pores within a given particle in the matrix (such as an individual piece of bark or a cellulose fiber) and the voids created when the particles are packed together, bridging and creating geometries. This is where overall averages and experimental measurements become important.

4.2.2 Equation of Continuity in a Porous Medium

The equation of continuity is derived by taking a macroscopic approach, defining a representative elementary volume (REV) with dimensions Δx, Δy, and Δz (L) (See Figure 4.1). This development is derived from Geankoplis (1993), Nield & Bejan (1998) and Jasmin (2000).

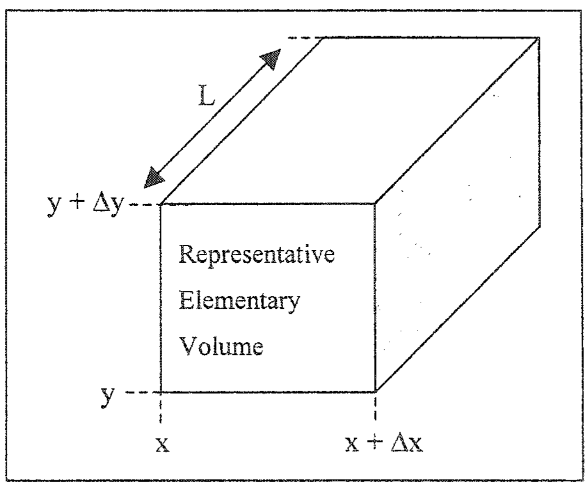

Figure 4.1: Representative Elementary Volume

Defining the velocity distributions along the x and y axis as u and v respectively, the mass flow, $\dot{m}$, of a fluid of density ρ passing through this REV becomes:

$$\dot{m}_x = \rho\int_y^{y+\Delta y}\int_0^L u(x,y)\,dz\,dy \tag{4.2}$$

$$\dot{m}_y = \rho\int_x^{x+\Delta x}\int_0^L v(x,y)\,dz\,dx \tag{4.3}$$

Here the concept of intrinsic velocity is introduced, which is essentially the average velocity throughout the REV, again along the x and y axis. It is assumed for these calculations that there is no flow in the z axis (L direction).

$$u = \frac{1}{L\Delta y}\int_{y}^{y+\Delta y}\int_{0}^{L} u(x,y)\,dz\,dy \tag{4.4}$$

$$v = \frac{1}{L\Delta x}\int_{x}^{x+\Delta x}\int_{0}^{L} v(x,y)\,dz\,dx \tag{4.5}$$

which allows us to write:

$$\dot{m}_x = \rho u(L\Delta y) \tag{4.6}$$

$$\dot{m}_y = \rho v(L\Delta x) \tag{4.7}$$

Taking the sum of the mass leaving the REV as well as the mass generated in time, subtracting the mass entering, and applying it to the available void spacing, *n*, the following expression is obtained:

$$\frac{\partial(\rho n L\Delta x\Delta y)}{\partial t} + \frac{\partial(\rho u L\Delta y)}{\partial x}\Delta x + \frac{\partial(\rho v L\Delta x)}{\partial y}\Delta y = 0 \tag{4.8}$$

Generation + Flow in x + Flow in y

Figure 4.2 illustrates the above equation.

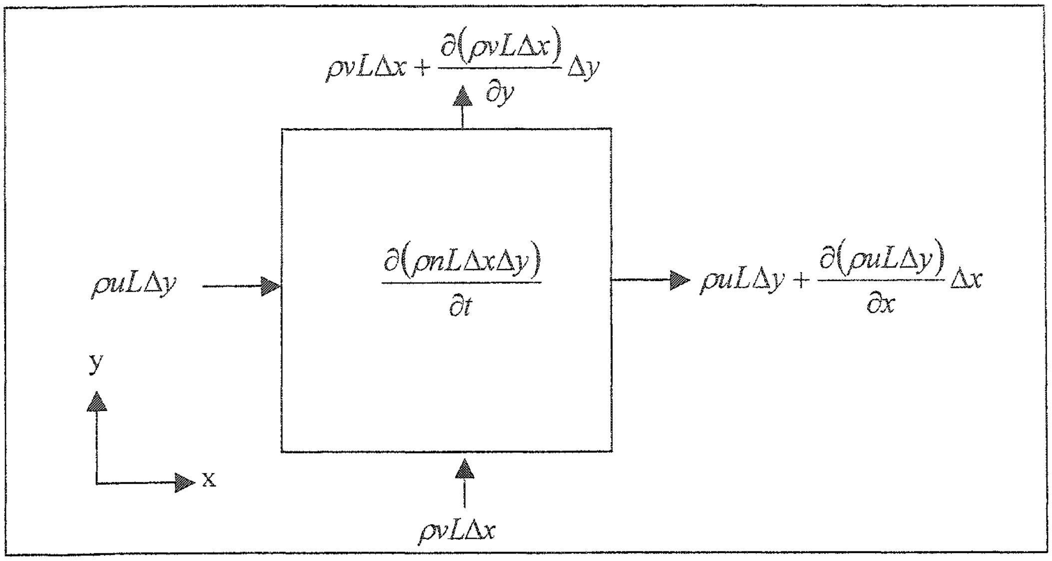

Figure 4.2 : Conservation of Mass on a REV

Dividing by the constant values $L\Delta x\Delta y$:

$$\frac{\partial(n\rho)}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}=0 \tag{4.9}$$

which, in three dimensions, becomes:

$$\frac{\partial(n\rho)}{\partial t}+\nabla(\rho\vec{V})=0 \tag{4.10}$$

where $\vec{V}$ is velocity. An understanding of the overall mass and energy flowrates into and out of a given volume allows for prediction of behaviour within a bulk material.

4.2.3 Momentum Equation

In porous media, the equation of momentum generally used is that of Darcy's Law. Darcy developed this equation empirically in his investigations of hydrology in Dijon, France (1856).

$$\vec{V}=-\frac{K}{\mu}\nabla p \tag{4.11}$$

Darcy's law is applicable for Newtonian fluids (like air) under laminar flow conditions. A more simplified version of Equation 4.11 is the Darcy equation for gas flow in one direction in a porous medium where gravity can be neglected as follows,

$$v = -\frac{K}{\mu}\left(\frac{\Delta P}{L}\right) \tag{4.12}$$

where v is the fluid velocity (fluid being air), μ is the viscosity of air, K is the permeability of the porous material, and ΔP is the pressure drop across a distance, L. The porosity and permeability can be related by empirical relation based on the material geometry (particle shape, average diameters, etc.) such as the Carman-Kozeny relationship for beds of particles or fibres (Nield & Bejan, 1998),

$$K = \left(\frac{D_p^{\,2} n^3}{180(1-n)^2}\right) \tag{4.13}$$

where D_p is the effective average particle or fibre diameter. Non-uniform shapes such as those of sludge agglomerates and bark are more difficult to relate. Darcy's law states that for laminar flow in porous media, the fluid flow (velocity or flowrate) is proportional to the pressure drop and inversely proportional to the fluid viscosity and the linear distance traveled. When working with (isotropic) biomass, it is often the permeability (K) that is unknown. Rewriting Equation 4.12 using the volumetric flowrate over a known cross-sectional area (A) allows for a calculation of the permeability to be made.

$$K = \frac{Q\mu}{A\left(\Delta P/L\right)} \tag{4.14}$$

It is important to note that Darcy's law applies only to laminar flow conditions, i.e. in the case of flow in porous media where Reynolds numbers (Re_k) are less than unity.

Equation 4.15 is the Reynolds number for flow in a porous medium (Nield & Bejan, 1998). Careful examination of this parameter is required in biodrying since the process employs fairly large air flowrates passed through the material to be dried.

$$\mathrm{Re}_K = -\frac{\rho v \sqrt{K}}{\mu} < 1 \tag{4.15}$$

It is important to note that Darcy's law does not balance all the forces over a given volume element, thus averages must be taken for the fluid (air) phase before taking into account drag forces caused by the individual particles. The Forchheimer (1901) equation can be added to Darcy's law (Equation 4.11), thus taking into account non-linear inertial forces that result from air losing momentum as it impacts fixed particles.

$$\vec{V} = -\frac{K}{\mu}\nabla p - \rho\frac{b}{\mu}\left|\vec{V}\right|\vec{V} \qquad (4.16)$$

where b is a dimensionless constant for form-drag.

4.3 – Transport Phenomena and Biological Activity in Aerobic Biopiles

The process under investigation in this study is an aerobic biopile. Although biomass drying is generally considered an empirically-described operation, there are multiple heat and mass transfer phenomena in the control volumes of a given biomass matrix. Moisture removal in liquid and in vapour form can be described. In the liquid form, water is transported by several mechanisms, the main ones being diffusion and capillary flow. Smaller migrations can be noted for flow caused by gravity, shrinkage of material, and pressure gradients. The vapour phase is also dominated by two transport mechanisms, namely convection and diffusion. Convection is related to the temperature, humidity and air flow of the carrier gas (usually air) as well as concentration (of moisture) gradients within the material to be dried, while diffusion is dictated by temperature gradients.

4.3.1 Transport Phenomena of Biodrying Process under Investigation

Liquid water is present in the biomass prior to drying, existing in both the bound and unbound states as described earlier. However, once sludge mixtures are dewatering to >25% solids, they possess little free unbound moisture, thus only the vapour phase water removal is considered in this treatment (i.e. no gravity trickling of liquid water). However, phenomena occur inside the biomass matrix involving liquid phase transport of water as well as the vapour phase transfer from liquid to air and vice-versa. Energy is also transported and generated within the system, and can be calculated over the whole process as well as at the REV level as treated in Section 4.2.2.

Figure 4.3 schematically illustrates the mix of sludge and bark treated in this study. This matrix of material is subjected to a flow of air (shown from left to right). The blow-up within Figure 4.3 magnifies various features of the materials, detailing individual fibres, small biosolids (flocs) and void spaces where interstitial water can reside.

The bound water is sequestered in various ways depending on the type of biomass. In bark, water is held within the small capillaries, voids and cracks of the material. In residual wood fibres, water can be present within the capillaries of the fibres and adhered to the surface. Within cells, water is present as a surface film and most importantly within the cell wall. This water is essential to the proper operation of the microorganisms, and cannot be removed without destroying the cellular membrane either physically (crushing, centrifuge, or similar) or through chemical and/or temperature techniques. This cellular bound moisture is typically the most difficult moisture to access, resulting in secondary sludge (containing mostly cellular material) that proves to be the most challenging material to dewater.

During drying, convective mass transfer occurs, removing surface water at a constant drying rate until the material surface cannot supply moisture. At this point, moisture must migrate from the interior of the individual particles to their surface for evaporation, otherwise known as the falling-rate period. The water flows through the different material components by way of diffusion and capillary flow.

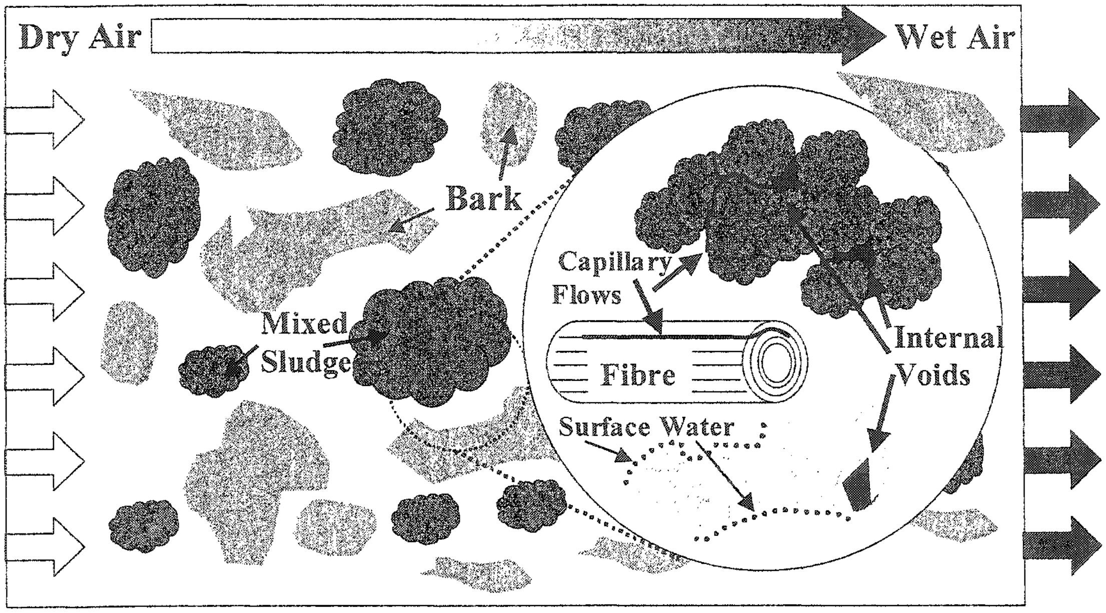

Figure 4.3: Mass Transfer Schematic

Constant Drying Rate Zone:

During the constant drying rate period, the rate of removal of the water vapour is controlled by the rate of heat transfer to the evaporating surface (biomass), which supplies the latent heat of evaporation for the liquid. During this phase of drying, the rate of mass transfer and the rate of heat transfer balance one another. The following development is derived from Geankoplis (1993).

HEAT TRANSFER:

The rate of convective heat transfer from the gas at temperature T, to the surface water at the wet bulb temperature, T_b, is

$$q = h(T - T_b)A \tag{4.17}$$

where q is the rate of convective heat transfer in W (J/s), h is the heat-transfer coefficient in $W/m^2 \cdot K$, and A is the exposed surface in m^2. It is assumed here that all water transfer is by convection, and no heat is transferred by conduction or radiation.

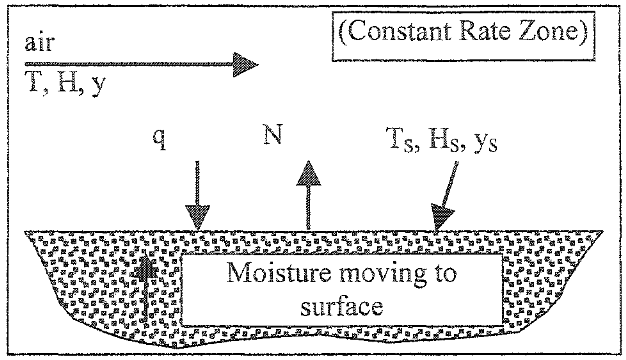

Figure 4.4: Heat and Mass Transfer for Constant Rate Drying

MASS TRANSFER:

This derivation for a flat plate geometry shown in Figure 4.4 is now presented. The mass transfer flux is described by the following:

$$N = k_y(y_S - y) \quad units > \left[\frac{kg\,mol}{s \cdot m^2}\right] = \left[\frac{kg\,mol}{s \cdot m^2 \cdot mol\%}\right] \bullet [mol\%] \qquad (4.18)$$

where N is the flux of water being removed from the solid, y is the mole fraction of water in air, and k_y is the mass transfer coefficient. The subscript S indicates conditions at the surface. Since y is related to the molecular mass (M) of air and water as well as the humidity in kg H_2O/kg dry air, H, by:

$$y \cong \frac{HM_{air}}{M_{water}} \qquad (4.19)$$

where the ratio of molar masses converts mass% to mol%, Equation 4.18 can be expressed as:

$$N = k_y \frac{M_{air}}{M_{water}}(H_S - H) \qquad (4.20)$$

The heat required to evaporate a flux of water, N can be described as:

$$q = M_{water} N \lambda_W A \qquad (4.21)$$

where λ_W is the latent heat of water at the wet bulb temperature.

Equating 4.17 and 4.21 and substituting 4.20 for N yields the rate of water removal by mass, R (kg $H_2O/s{\cdot}m^2$), as follows:

$$R = \frac{q}{A\lambda_W} = \frac{h(T - T_S)}{\lambda_W} = k_y M_{air}(H_S - H) \tag{4.22}$$

It has been found that the heat transfer equation is the most useful for calculation of the drying rate (Geankoplis, 1993), that is:

$$R = \frac{hA}{\lambda_W}(T - T_S) \text{ [kg } H_2O \text{ / s]} \tag{4.23}$$

For drying calculations, it can be convenient to express the rate of drying in terms of a decrease in moisture content rather than water loss. For evaporation from a tray of wet material of depth, d and bulk density ρ_b and constant volume, Equation 4.23 becomes

$$R = \frac{h}{\lambda_W d\rho_b}(T - T_S) \text{ [kg } H_2O \text{ /s·kg dry solids]} \tag{4.24}$$

These equations are for a simple flat plate. However, in porous media, the surface area is substantially larger than for a flat plate, requiring some changes. For flow circulation up through a bed of material, a similar equation to 4.24 can be written (Geankoplis, 1993):

$$R = \frac{ha}{\lambda_W \rho_b}(T - T_S) \text{ [kg } H_2O \text{ /s·kg dry solids]} \tag{4.25}$$

where a is the equivalent surface area per unit of material volume (m^2 / m^3 = 1/m). This value is difficult to estimate without experimental data. Correlations exist for ideal (spherical and cylindrical) shapes (Porter, 1984).

Falling Drying Rate – Diffusion & Capillary Flow Zones:

During this period, there is no longer any free unbound surface water, and the rate of drying is substantially lower. Referring to Figures 4.3 and 4.4 for the case of a biomass matrix, once the surface water is removed, it must then migrate from within sludge, bark and fibers to the surface to be removed. This is done primarily through diffusion, and to a lesser degree, capillary flow.

Diffusion:

Moisture diffusion within a solid particle will be the rate-determining step in the falling drying period because water that arrives at the surface will be removed almost immediately. Diffusion in the solids takes place according to Fick's second law of diffusion:

$$\frac{\partial X}{\partial t} = D_{AB}\frac{\partial^2 X}{\partial x^2} \qquad (4.26)$$

where X is in units of kg free moisture/kg dry solid, x is the distance into the solid, and D_{AB} is the diffusivity of components A and B (water and air through the solid in m^2/s). For liquids, this value becomes D_L, the liquid diffusion coefficient. For a slab of material of thickness x, dried from both sides (similar to a flat piece of bark), the ratio of the average moisture content (X) to the initial free moisture content X_i is as follows:

$$\frac{X}{X_i} = \frac{8}{\pi^2}e^{-D_L t(\pi/2x)^2} \qquad (4.27)$$

which can be solved for time of drying to become the following:

$$t = \frac{4x^2}{\pi^2 D_L}\ln\frac{8X_i}{\pi^2 X} \qquad (4.28)$$

This can be differentiated with respect to time to yield:

$$\frac{dX}{dt} = \frac{\pi^2 D_L X}{4x^2} \qquad (4.29)$$

From this, it can be said that the rate of drying is proportional to the free moisture X and the liquid diffusivity, and inversely proportional to the square of the particle (slab) thickness. It should be noted that these derivations assume constant diffusivity, when in fact, the rate of diffusion changes with moisture content, temperature, and humidity.

Capillary Flow:

If the geometry of the porous space between particles is suitable, moisture may move from an area of higher concentration to one of lower concentration by capillary action rather than by diffusion. As water is removed from the porous media, the curvature of water films is increased within void spaces, resulting in suction pressures that in turn transport water. Geankoplis (1993) presents an equation for the time of drying if capillary flow controls the falling rate period:

$$t = \frac{x\rho_S \lambda_W X_C}{h(T - T_W)} \ln \frac{X_C}{X} \tag{4.30}$$

where ρ_S is the solid density (kg/m^3)and X_C is the critical moisture content, the point at which there is no longer enough water at the surface to sustain a continuous film.

In general, capillary action will be the first liquid transport phenomena observed once the constant rate period has ended. The dry surface is replenished by capillary flow, siphoning water from within the biomass particle. When there is insufficient flow for capillary action to maintain a film of water, then diffusion and conduction may become the main factors in the solids drying.

Further work on drying of biomass particles has been completed by Zabaniotou (2000), Gigler et al. (2000), and Saasramoinen and Impola (1997). These authors go into further detail with mathematical models of drying for both constant rate and falling rate zones. Diffusion in wood chips in particular is discussed by Gigler et al. (2000).

4.3.2 Thermophilic Aerobic Biological Activity in Biopiles

Composting technology refers to the method of achieving thermophilic aerobic biological activity in biopiles, and is a method of solid waste management in which organic material is biologically decomposed under controlled conditions to a state in which it can be handled, stored, and/or applied to the land as a useful and beneficial soil amendment without adversely affecting the environment. Sludge may be mixed with a bulking agent to absorb moisture and assist aeration. As bacteria decompose the organic matter, the biopile heats up. The U.S. Environmental Protection Agency (EPA) requires that sludge compost piles reach and maintain a temperature of 55°C for a minimum of three days (EPA, 1987), primarily to kill pathogens. If aerobic conditions are not maintained within the mixture, odour can become significant. The main parameters to consider in an aerobic degradation process are the microbiology, oxygen, nutrient and moisture requirements.

Microbiology:

Wide ranges of microorganisms (bacteria, actinomycetes and fungi) metabolize organic compounds in waste; however, not all the decomposition of organic material in composting is biological in nature. Chemical and physical conditions also have an influence. The physical, biological, and chemical decomposition processes are so complex that it becomes difficult to ascertain exactly how these processes are interrelated because they are in a continuous state of change. For example, a slight change in temperature will cause some microorganisms to flourish and others to die. The microbiological strains found in a composting environment are highly varied. The effectiveness of bacteria and fungi in decomposing the organic material is based on the operational conditions of the composting system. The ideal temperature range for composting to take place is between 35°C and 65°C (Naylor, 1996). This encompasses a range of different groups of organisms that can be categorized based on their temperature tolerances. Figure 4.5 shows some of the ranges covered by four main groups of microorganisms: the psychrophiles, the mesophiles, the facultative thermophiles, and the thermophiles.

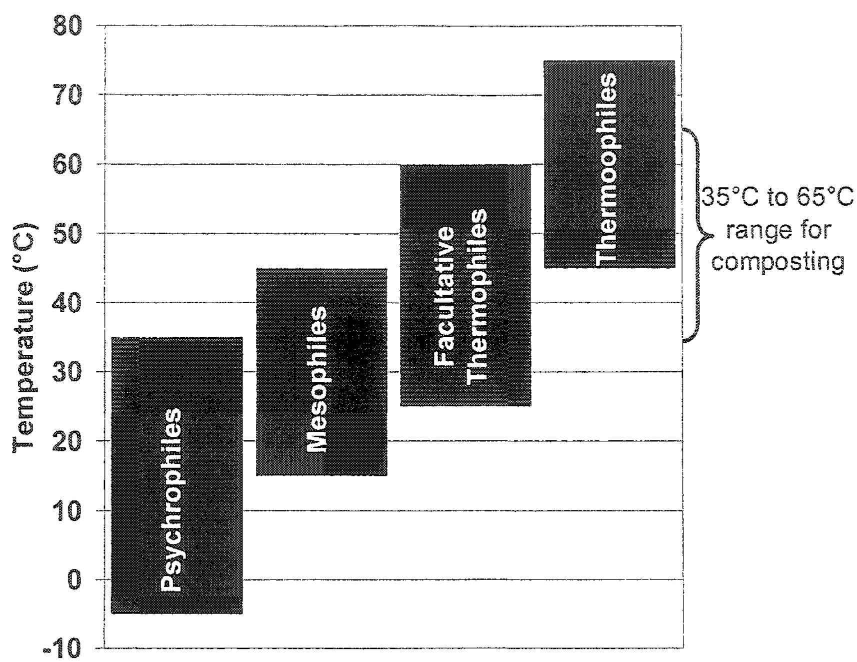

Figure 4.5: Temperature Tolerances for Various Groups of Organisms (Adapted from Naylor, 1996 and Pelczar, 1972)

For moisture removal, it is preferable to have temperatures as high as possible, thus thermophilic microorganisms are the most desirable.

Oxygen Requirements:

Aerobic biodegradation requires uniform and sufficient oxygen transfer to ensure that microorganisms are able to respire at optimum levels. Aeration rates for a compost pile should be adjusted to keep oxygen percentages between 5-15% O_2 as compared to 21% in air (Campbell et al., 1991). This translates to about 1 to 4 grams of oxygen per gram of biodegradable material (or ~ 4 to 17 grams of air per gram of material) (Haug, 1993). However, these values represent only the oxygen required for metabolism. When drying of the material is considered (as with the biodrying application of this work), the aeration rates are far in excess (10 to 30 times) of those required for biological oxidation (Haug, 1993). Air must be properly diffused and be able to reach all pockets of material. Sometimes air will not be able to penetrate into clumps of material (sludge for example), resulting in local anaerobic conditions. This is why special care must be taken in the type and quantity of bulking agents used, in the pre-treatment of the material before it enters the reactor (size reduction, clump breaking, etc.), and the methods of oxygen distribution to the biopile.

Nutrients:

Sufficient concentrations of key nutrients (nitrogen, phosphorus, sulfur, and other trace nutrients) are required by organisms for proper cell growth. The carbon to nitrogen ratio is the most often cited nutrient parameter. The ideal range for composting is a 20:1 to 40:1 C:N ratio (Campbell et al., 1991; Naylor, 1996). In the pulp and paper industry, nutrient carryover from the wastewater treatment facilities typically meets the needs for composting. Table 4.1 shows some data for C:N ratios in a variety of materials.

Table 4.1: C:N Ratios for Various Biomass Materials

Biomass Material	C:N Ratio	References
Primary Sludge	32-930 : 1	Thaker, 1985
Secondary Sludge	9-81 : 1	Shimek, 1988
Combined Sludge	6-115 : 1	Scott, 1995
Wood Chips	492-535 : 1	McBurney, 1993 Durai-Swamy, 1991
Waste Paper (fibre)	487 : 1	Kara, 1994
Bark	160-534 : 1	James, 1991 McBurney, 1993

Different mixtures of biomass substrates (sludge, bark, etc.) will result in unique C:N ratios as evidenced by Table 4.1. While secondary sludge has a very low C:N ratio, materials such as bark and fibre possess little nitrogen and therefore very high ratios. Larsen et al. (2000) found a negative linear correlation between heat generation and the C:N ratio for paper mill biosolids, with high levels of heat generation occurring for C:N < 40. As the amount of bulking agent (bark) increases, the C:N ratio will also increase, so the amount of heat generation must be balanced against the increased porosity that the bulking agent provides.

Moisture:

Moisture is vital to the proper functioning of the microorganisms. The cell membranes must remain permeable to a steady flow of soluble nutrients by osmosis (Naylor, 1996). Moisture contents of biopiles should be in the range of 40-70% (Campbell et al., 1991; Naylor, 1996; Haug, 1993). If the moisture content is too high, oxygen will have difficulty traveling through the system, and if it is too low, the organisms exhibit reduced performance. With composting, the goal is to produce a stable product, so moisture is added or removed as required to achieve the desired operating conditions. In the case of biopile technology for drying of biomass such as in this study, *supplemental* water will not be added because the goal is to dry the material and not to produce a stable product for use in soil. The feed material has adequate moisture concentrations that are reduced through time. When the reaction begins to slow due to lack of moisture (<40%), the product is dry enough for combustion.

4.4 – Context of Transport Phenomena in Process under Investigation

It is useful to differentiate between composting and biodrying, which approach carbon consumption in opposing ways. In composting the goal is to degrade the easily accessible organic compounds, resulting in a decomposed soil amendment. Operating temperatures are high and oxygen is supplied only in the amounts required to meet the respiration needs of the microorganisms. In biodrying, large amounts of excess air are supplied in order to meet the respiration needs as well as to carry off excess moisture. Biological activity remains the same, but process temperatures are kept lower due to the increased airflow. The carbon consumed throughout composting process results in a product with reduced calorific value, unsuitable for combustion for energy reclamation. In biodrying, carbon losses are minimized (through shorter residence times and moisture limitations) and energy content is increased by 30% to 40% because of the moisture removal. Therefore, composting (or biodegradation) and biodrying are inversely correlated (Adani, 2002). Biodrying can be termed as "accelerated composting" in that the heat and mass transfer phenomena occur at increased rates (i.e. water and microbial heat are removed in greater quantities than with a static or lightly aerated composting process).

A biodrying process would need to address differences between constant and falling rate drying periods. In the constant-rate zone, water is present primarily as surface moisture and can be removed through convection. Since convection is a function of temperature and flowrate, drying is achieved using as large an airflow as possible while maintaining saturated air at the outlet of the system. As the surface moisture is depleted, diffusion and capillary forces act to transport moisture from within aggregates to their surface. These processes are slower than for convective transport, and the flowrate will be reduced accordingly. Maintaining the outlet air saturated at 100% relative humidity is a good control parameter for the system. As free moisture is depleted, the flow will reduce to a minimum value accordingly. This minimum will at the very least supply oxygen to the microorganisms, however the flowrate will also need sufficient pressure (velocity) to reach all points within the matrix, to remove moisture at a reasonable rate and maintain saturation.

5.0 – SOCONAG - SMARTSOIL™

5.1 – History

SOCONAG is a Canadian company founded in 1985 whose mission is to design, construct, and commercialize industrial biological reactors that accelerate the transformation of forestry, agricultural, and industrial residues into recycled material and renewable energy. This thesis represents a new application of SOCONAG's SmartSoil™ technology to address the important industrial problem of sludge disposal by combustion.

SmartSoil™ technology is a specific configuration that allows for the real-time acquisition and control of process fluid flow (both air and water) as well as other operating parameters for porous media systems. The SmartSoil™ system consists of the treatment apparatus, data analysis software, as well as patented sampling and measuring systems. The mechanical, electric, and information system components of the SmartSoil™ system are patented in Canada and the United States, as well as Europe and Australia. These components are adaptable to reactors that vary in size from a few tonnes at the laboratory scale to 10 million tonnes for a solid waste disposal facility.

Implemented SmartSoil™ systems treat up to 2,000 tonnes of contaminated soil per year, 1,000 tonnes of compost per month, and up to 500,000 tonnes of municipal solid waste over a period of 20 years.

The SmartSoil™ system collects data from multi-level, multi-parameter sensors known as MAProbes™ installed directly within the porous media being treated. A control system interprets this data and determines the appropriate commands to transmit to the aeration systems to optimally control the airflow patterns. This unique system of pressure acquisition, data interpretation, and aeration control allows SmartSoil™ technology to be considered an excellent tool by researchers and industrial operators.

5.2 – System Components

Biopile systems are relatively simple. Some of the main capital cost items for a biopile system incorporating SmartSoil™ technology are:

Reactor(s): vessel(s) used to hold large volumes of biomass to be treated (concrete or steel structure)

Blowers and Piping: for injecting, extracting and distributing air; included here are valves, heat exchangers, diffusers, and associated electrical systems

SMARTSOIL™ Technology: comprises the key control elements (both instrumentation and software)

Material Handling: for mixing, adding and removing biomass from the reactors; can range from front-end loaders to full conveyor application and traveling screw reclaim.

5.3 – Industrial Applications

SmartSoil™ technology has been applied to a variety of commercial contracts in the following fields, from pilot to full scale:

- batchwise treatment of contaminated soils
- biogas extraction from landfill sites
- batchwise composting

Biological Decontamination of Hydrocarbon Laden Soils: SmartSoil™ has been used at various scales for the decomposition of contaminated soils. The system allows for savings related to space while also minimizing the amount of liquid and gaseous effluent from the by-products of decomposition. For example, a SmartSoil™-Biopile system was installed on a platform located in a town to the north of Québec city that could treat 6,000 tonnes per year of contaminated soil. The system allowed for a 50% reduction in treatment time compared to traditional methods as well as decontamination of complex hydrocarbons.

Landfill Gas Extraction: Soconag's spin-off company, SmartSoil-Energie^{TM} operates a 200,000 tonne municipal solid waste gas extraction facility. Within the landfill cells, anaerobic conditions prevail. SmartSoil-Biogaz^{TM} re-injects biogas with the goal of increasing the internal flowrates and dislodging unused pockets of methane. The system produces 50% greater flowrates of biogas compared to traditional vertical pipe reclamation systems, and with more consistent methane concentrations. Once extracted from the system, the gas is flared to convert methane into CO_2 and water. Future plans involve system expansion and piping the gas to a gas turbine to produce electricity.

Composting: SmartSoil^{TM}-Compost allows for excellent composting performance that requires no pile turning, low odour production, and reduced treatment times at high operating temperatures (>60°C). A large scale test (500 m^3) was conducted on a mixture of forestry residues (sludge, biosolids, and bark). Process air was injected and extracted with the SmartSoil^{TM} system, resulting in a composting time of only 3 weeks.

6.0 – SLUDGE DRYING USING BIOPILE TECHNOLOGY

As discussed, the SmartSoil^{TM} technology is an effective solution for the control of flow through porous media. Given its applicability for accelerated composting and for handling large quantities of biomass, the technology could be applied to the solid waste management challenge at hand. In the current work, it is proposed to dry pulp and paper mill sludges under aerobic thermophilic conditions using an aerated biopile. This "biodrying" application utilizes the principles of composting combined with increased and optimized aeration to promote water removal instead of substrate degradation. In this way, mill sludge can be dried to levels which make disposal in the mill's power boiler attractive, that is, with greater than 50% solids content. The energy input to the system is restricted to aeration and material handling power. Heat energy for water removal is provided by thermophilic microorganisms rather than fossil fuels or other heating sources, which sets this drying approach aside from the traditional methods outlined in Section 3.

In the process investigated, mixed dewatered sludges from the mill's existing treatment facilities are combined with bark as a bulking agent. Preliminary work on this process concept was accomplished using a batch reactor configuration in order to determine the drying and pneumatic characteristics of the sludge/bark mixture and to determine proper bulking ratios for effective operation. The mixture was introduced into a reactor with a volume of 1 cubic meter (1 m^3). These dimensions were selected to reduce the size effects of individual bark and sludge chunks while providing a reasonable experimental apparatus. The dried material was removed after an allotted treatment time. Three aeration conduits ran along the bottom of the reactor and the mixed material was placed on top of them. Within this matrix were temperature and pressure acquisition points to characterize the internal parameters during operation. Airflow, relative humidity, and mass data were collected as well and analyzed in a central data acquisition system. Section 7 will elaborate on the experimental set-up and protocol.

6.1 – Techno-Economic Considerations for Biodrying

Given the potential of biodrying, the task lies in applying it to the industry in an innovative and cost-effective fashion. No two mills are alike when the layout, technology, and operating philosophy of each installation are considered. Therefore, each application of biodrying technology will require a unique approach to determine how it will best meet the needs of the facility.

At this early stage of development for the technology, a techno-economic analysis of the process is prudent to determine the conditions under which biodrying is technically viable. A model of the biodrying system was developed that looks at the relative importance of various operating parameters (residence time, atmospheric conditions, bulking ratios, etc.) to gain better understanding of the applicability of this process to various hypothetical and real mills. These preliminary screening steps identify which mills would benefit from a biodrying installation and those that would find it challenging to implement.

Section 8 outlines the context of the techno-economic analysis, compares the applicability and return on investment for various operating scenarios, and identifies which parameters have the most important effects on the process.

7.0 – BENCH-SCALE BIODRYING EXPERIMENTS

It should be noted that some material in this section is contained in manuscripts that have been accepted for publication in the peer-reviewed journal of Drying Technology (1.Frei et al., 2004) and as a Paprican University Report (2.Frei et al., 2004) (see Appendix I).

In order to investigate the feasibility of the proposed biodrying process, three batch experiments were conducted. The main objective of these experiments was to determine the drying characteristics for a (batch) biodrying configuration fed with mixtures of pulp and paper mill sludges (primary/secondary mixtures) and woodwaste, such that:

- reliable mass balances for water and carbon loss could be completed
- an appropriate sludge to woodwaste mixing ratio could be determined which results in acceptable pneumatic performance
- preliminary results (without process optimization) with respect to overall process performance and drying rates could be obtained
- information could be obtained regarding how the process efficiency might be improved with improved reactor operation and/or design

7.1 - Materials and Methods

7.1.1 Raw Material Characteristics and Preparation

The mixed sludges and woodwaste were supplied from a wastewater treatment facility and related operations of an integrated pulp and paper mill in northern Quebec. This mill produces a range of products from pulp to board to ethanol. Mixed sludge production from the mill is approximately 100 dry tonnes per day, with an average solids content of 26%. The mixed sludge is composed of 30% biological sludge and 70% primary sludge.

Sludge and woodwaste were collected on-site and shipped in large (500L, 1000L) containers, taking approximately 36 hours to arrive in Montréal. Upon arrival, the sludge and woodwaste were mixed based on mill information concerning the dryness levels of the material shipped, which was later confirmed by moisture content analyses performed on samples sent to an outside laboratory. Mixing had to take place immediately in order to avoid premature material decomposition and to limit odours produced during transport. Table 7.1 summarizes the sludge mixtures for the three experiments, including the difference between the target and actual mixing ratios achieved, the bulk density, and the amount of biological sludge contained in the mixed sludge samples (data supplied by mill).

Table 7.1: Sludge and Woodwaste Characteristics for Each Experiment

	Experiment #1	Experiment #2	Experiment #3
Target Mixing Ratio (dry basis)	1:1 (sludge:bark)	1:0.5	1:0.25
Actual Mixing Ratio (dry basis)	1:1.4	1:0.6	1:0.3
Avg. Initial Sludge Solids*	30.4%	23.7%	21.3%
Avg. Initial Woodwaste Dryness*	80.0%	62.6%	53.5%
Mixed Sludge Biological Content**	26% (average)	17% (low)	45% (high)
Initial Mixture Solids***	47.5%	30.5%	24.5%
Mixed Sludge Bulk Density	~ 550 kg/m^3	~ 600 kg/m^3	~ 800 kg/m^3
Mixed Sludge Description	Dry, chunky	Wet, fluffy	Heavy, wet
Woodwaste Description	Very dry bark	Dry, sawdust-like bark	Moist, sawdust & stringy bark
Overall Matrix Characteristics	-Strong porous matrix structure -Easy air passage -Little compaction	-Homogeneous mixture -Uniform, small particles led to good pneumatic conditions	-Difficult to mix, resulting in dense matrix -Worst case mixture, almost pure sludge

Notes:
* Based on 3 composite samples
** From mill data on day of sampling
*** Initial dryness from composites, not calculated

There were three different mixed sludge compositions and three bark types, whose range of characteristics would be important to consider in the design of a full-scale system. The first experiment consisted of mixed sludge with a typical secondary sludge content of 26% and a relatively high sludge dryness of ~30%. This resulted in sticky balls of mixed sludge ranging in size from 2 to 10 cm diameter. The bark for this experiment contained higher than usual, large pieces of material that were removed and broken up during mixing to create a more homogeneous mixture. The mixed sludge for the second experiment was wetter (~24%), had a lower secondary sludge content of 17%, and was consequently fluffier. The bark sample consisted of large wood chunks mixed with sawdust. The third experiment of mixed sludge was the wettest (~21%), and had the highest secondary sludge content of 45%. This sludge had a mud-like consistency, making it difficult to mix with the small amounts of bark required for the target 1:0.25 mixing ratio. The two materials were mixed by hand with shovels, weighed and then fed into the reactor. From Table 7.1 it can also be seen that the initial matrix dryness for the 3 experiments was quite different (47.5%, 30.5%, and 24.5%). Initially the goal was to dry the matrix to about 50% (a level that would be appropriate for combustion), however given the high initial dryness of the 1st run, it was decided to dry to a higher level. It was therefore decided that the experiments would be run until the measured dry solids was 20 points higher than the starting point (e.g. 47.5% to 67.5%).

7.1.2 Reactor Set-Up and Experimental Procedures

The 1 m^3 biodrying reactor used for these experiments is shown schematically in Figure 7.1, and was provided by SOCONAG Inc. Two conduits are located on either side of the reactor and one in the middle. With this patented configuration and appropriate valving, the centre conduit alternately pushes and pulls air, while the two side conduits do the opposite. Temperature (T), pressure (P), relative humidity (rH) and air flowrates were measured in the inlet and outlet air flows. Within the reactor, data were collected at 18 pressure and 9 temperature points. The reactor was separated into two halves, called *A* and *B*, with multi-level probes located at the center point of each half (probes A & B). The mass of the complete reactor was monitored through four 0-1000 kg load cells. During each data acquisition cycle (approximately 10 min.), data from the various sensors were collected and analyzed, and the air flowrate was adjusted in order to maintain a constant and equal flow into and out of the reactor.

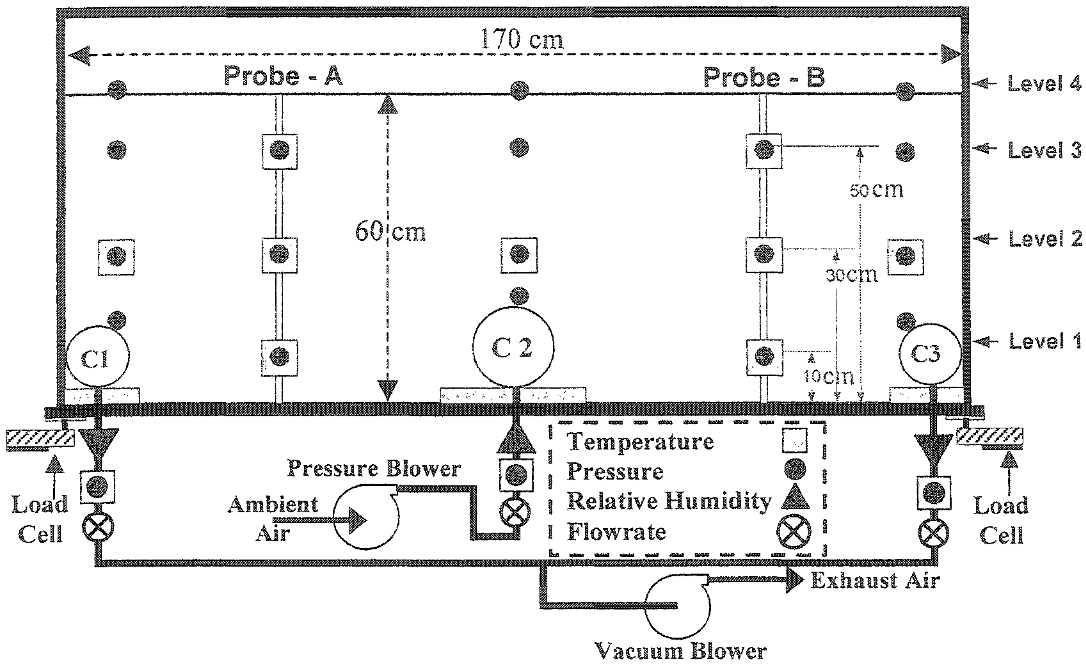

Figure 7.1: Biodrying Reactor Schematic

The reactor was filled with mixed sludge and woodwaste to a height of 60 cm, and then covered with a plastic membrane in order to seal the system for mass balance purposes. Aeration was applied such that the two side conduits operated opposite to the center one. That is, when the center conduit was injecting (+) air, the two side conduits would be extracting (-) air. The system was started in the negative flow configuration (shown as "+ – + " in Figure 7.2) and flows were adjusted to maintain a slight vacuum (0.005" H_2O) in the headspace above the matrix. This flow configuration was changed approximately every third day to minimize the formation of preferential pathways, and to redistribute the humidity front within the matrix being dried. In order to test the effect of the bulking ratio on the drying performance of the reactor, airflow was kept constant at ~25 SCFM (standard cubic feet per minute) +/- 2 SCFM for all the experiments. Feed air was taken directly from the laboratory and was subject to some variation in temperature and relative humidity depending on the time of day. Feed temperatures ranged between 20°C and 30°C and relative humidity between 15% and 50%.

7.2 – Results

7.2.1 Mass Balance Results

The rate of moisture loss was determined in two ways, as follows:

- by measuring changes in the total mass of the reactor with time using the load cells
- by calculating a water balance based on the relative humidity's of the injected and extracted air streams

The first method includes mass loss due to both carbon loss (from biological activity) and moisture loss (from drying), while the second method accounts for moisture removal alone.
The mass flow of water in the air streams at any point in time was determined using measurements for the relative humidity, flow and temperature of air with time, as follows:

Mass Flow of Water = Absolute Humidity * Airflow * Wet Air Density *(7.1)*

$\mathbf{R}_{in/out}$ [kg H_2O/min] = **H** [kg H_2O/kg dry air] * **Q** [m^3/min] * $\boldsymbol{\rho}_{wet\ air}$ [kg dry air/m^3] *(7.2)*

where the absolute humidity **H** is calculated using the relation:

$$H = \frac{18.02}{28.97} \cdot \frac{p_A}{p - p_A} \tag{7.3}$$

where **p** is the atmospheric pressure [Pascals] and $\mathbf{p_A}$ is the partial pressure of water vapour [Pa], calculated using:

$$p_A = \frac{H_R}{100} \cdot p_S \tag{7.4}$$

where $\mathbf{H_R}$ is the measured relative humidity [%] and $\mathbf{p_S}$ is the vapour pressure of water [Pa] at the measured temperature T [K]. Finally the wet air density is determined using the following:

$$\rho_{wet\ air} = \frac{1}{\frac{22.41}{273} \cdot T \cdot \left(\frac{1}{28.97} + \frac{1}{18.02} \cdot H \right)} \tag{7.5}$$

Figure 7.2 shows the mass balance results for moisture into and out of the reactor. The feed air brings in a relatively constant amount of moisture, while the outlet air stream carries with it water removed from the matrix. This generally resulted in a saturated or near-saturated air stream out of the reactor and the rate of moisture removal indicated by the thin black (middle) line in Figure 7.2.

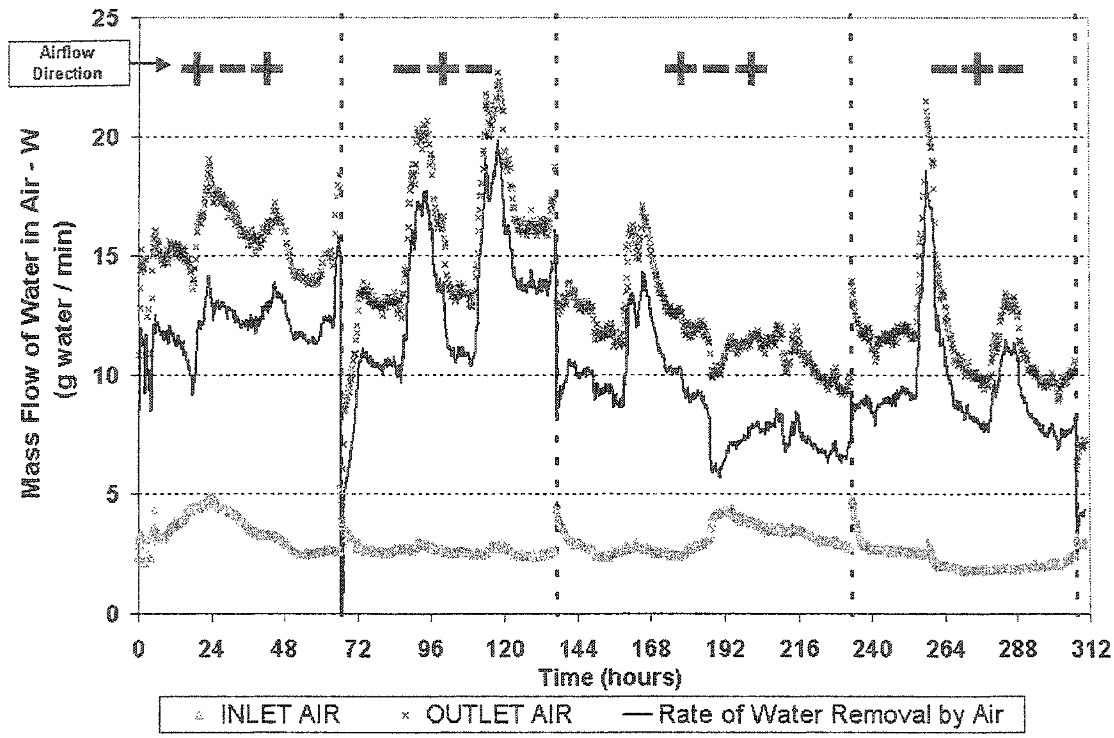

Figure 7.2: Water Mass Balance Into and Out of Reactor - Experiment 2

Local spikes in water removal can be seen in Figure 7.2. Although several factors affect the moisture content of air, these oscillations were most strongly correlated with the feed air temperature. Daily fluctuations in laboratory conditions (the effect of sun coming through the windows and heating the room) caused changes in the feed temperature. It is possible that the increased temperatures affected the moisture content of the exit air. This also indicates that the scale of the reactor possibly did not allow sufficient residence time in the reactor for the aeration air temperature to approach the matrix temperature. Therefore the increase in moisture content as air passes through the matrix is primarily from increased humidity (convective transfer).

Two methods were used to determine carbon balances:

- by measuring the dry solids of representative matrix samples (which were collected in a grid pattern within the reactor and then mixed to provide a composite sample), calculating the total mass before and after each experiment, and assuming all losses of dry mass were carbon
- by the difference between the total mass loss (measured by load cells) and the estimated moisture loss calculated psychrometrically (see Figure 7.3)

Table 7.2 summarizes the amount of water and carbon removed during the second experiment calculated with these two methods, and shows very good consistency in the overall mass balance results.

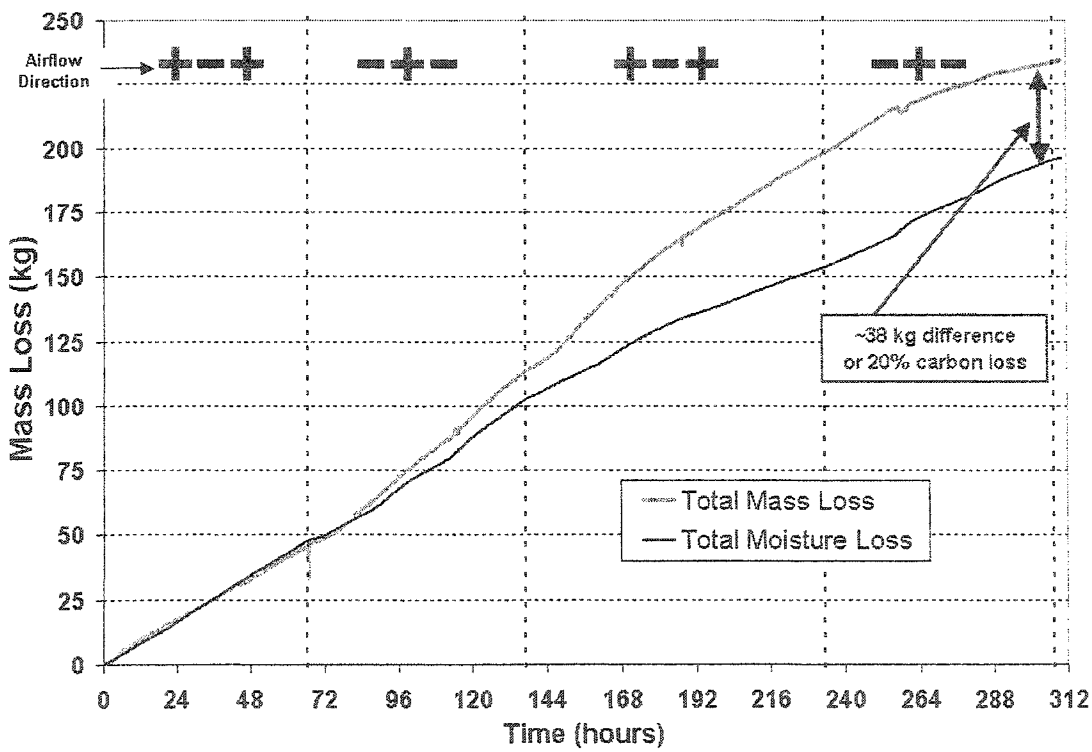

Figure 7.3: Estimate of Carbon Loss from Mixed Sludge - Experiment 2

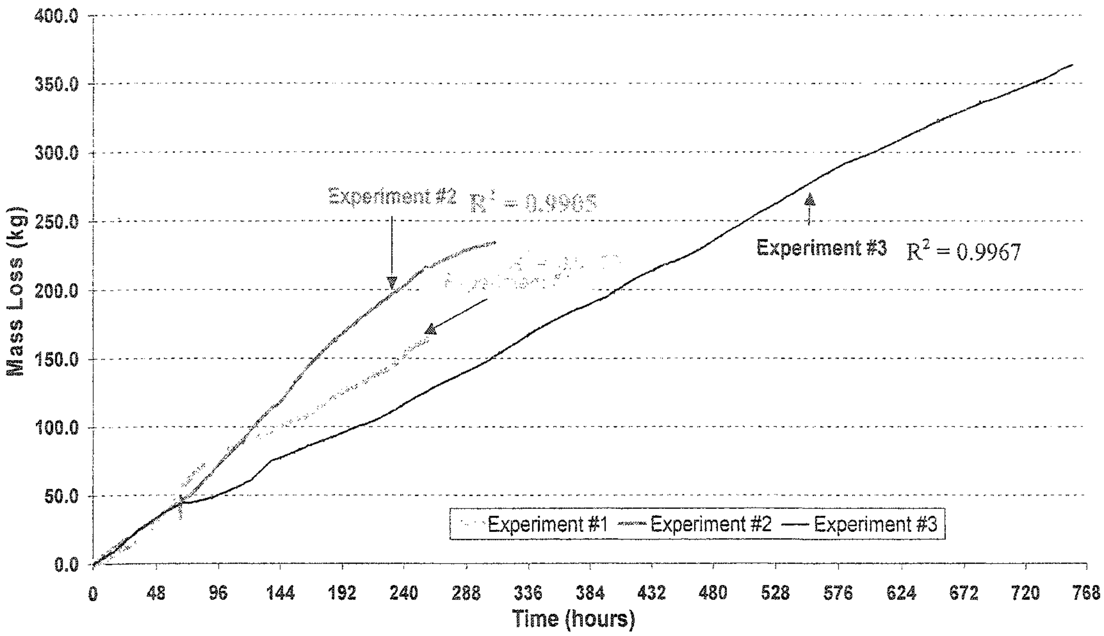

Figure 7.4: Total Mass Loss of All Three Experiments

Table 7.2: Carbon and Moisture Loss from the Matrix Calculated with Different Mass Balance Assumptions

ASSUMPTION	Carbon loss estimate by matrix dryness testing	Carbon loss estimate by moisture and total loss measurements
Experiment #1		
Carbon (solids) Loss	4%	3%
Water Loss	55%	56%
Experiment #2		
Carbon (solids) Loss	16%	20%
Water Loss	48%	46%
Experiment #3		
Carbon (solids) Loss	12%	13%
Water Loss	58%	58%

7.2.2 Matrix Drying Characteristics

Figure 7.4 shows the mass loss over time of all three runs. All the sludge/bark mixtures reduced in mass (primarily from removed moisture) at constant rates. R^2 regression values are also shown on Figure 7.4 and show strong linear correlations (all greater than 0.97). This graph also shows the difference is experimental run times, with the first experiment reaching it's target soonest and the third taking longest. The slopes of the curves are also slightly different, indicating variation in the rate of mass removal.

Figure 7.3 plots the moisture and carbon mass balances for the second experiment. The two curves begin to diverge as the experiment progresses, indicating an accumulating carbon loss in the form of CO_2 from biological activity. The slopes of the two curves in Figure 7.3 provide the rate of moisture and carbon removal with time, as presented in Figure 7.5(A). Both curves indicate a relatively constant removal rate initially, which increases as microbial activity increases and the matrix temperature rises (more so for the total mass loss than the water loss). There is an increase in the relative humidity of the outlet air to 100% corresponding to the sustained period of high biomass matrix temperature of about 40°C, trailing off at the end of the experiment when temperature falls off (see Figure 7.5(B)). Note that the relative humidity of the outlet air drops briefly after changes in air flow direction, likely indicating that dried solids are being re-hydrated by the humid air. When observing the two rate curves in Figure 7.5(A), the largest difference (indicated with arrows) is observed following changes in airflow direction, for a period of 10-20 hours as biological activity increases (likely due to the sludge rewetting).

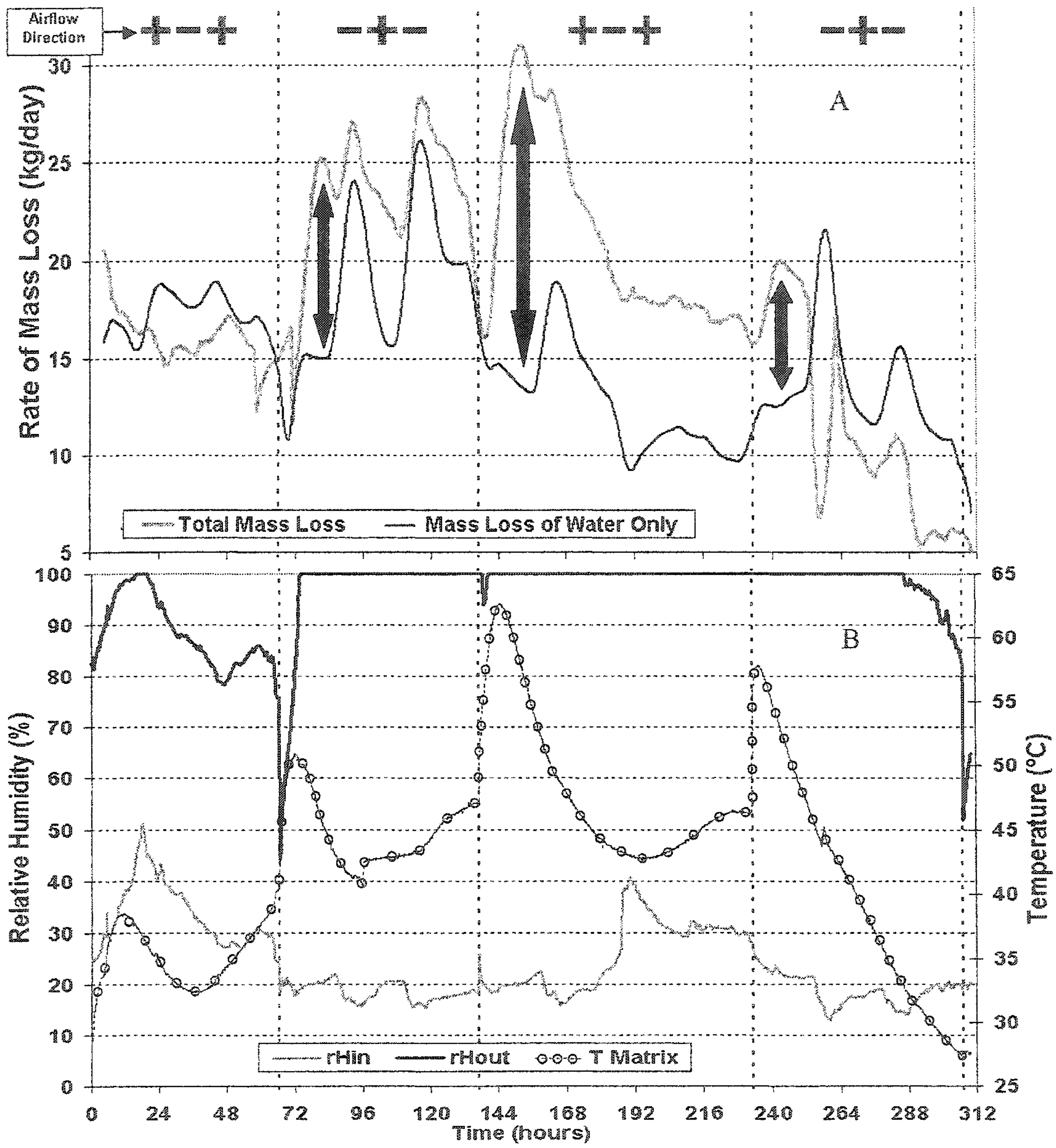

Figure 7.5: Comparison of (A) Total Mass Loss and Water Loss with (B) Inlet and Outlet Air Relative Humidity and Matrix Temperature - Experiment 2

The average temperature within the matrix can be correlated to the rate of total mass loss from Figure 7.5(A&B), as presented in Figure 7.6, which presents data for experiment 2. The two curves clearly follow one another. The increased outlet air temperature (as a consequence of the biological activity) allowed for the air to hold greater quantities of moisture, thus increasing the rate of drying. The importance of the exothermic biological heating contribution is not specifically analyzed in these experiments. The temperature increase proves that there is heating present and that it is important for the diffusional rate transfer processes. Figures 7.7 and 7.8 show that similar phenomena were observable in runs #1 and #3.

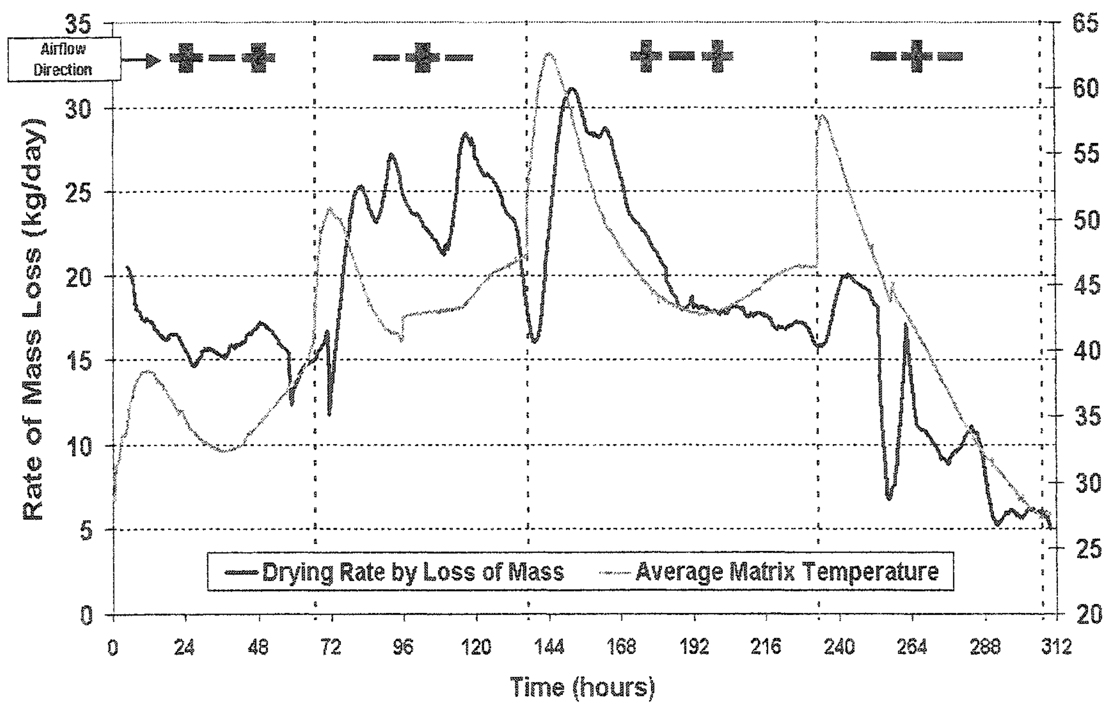

Figure 7.6: Average Internal Matrix Temperature Comparison with Rate of Drying - Experiment 2

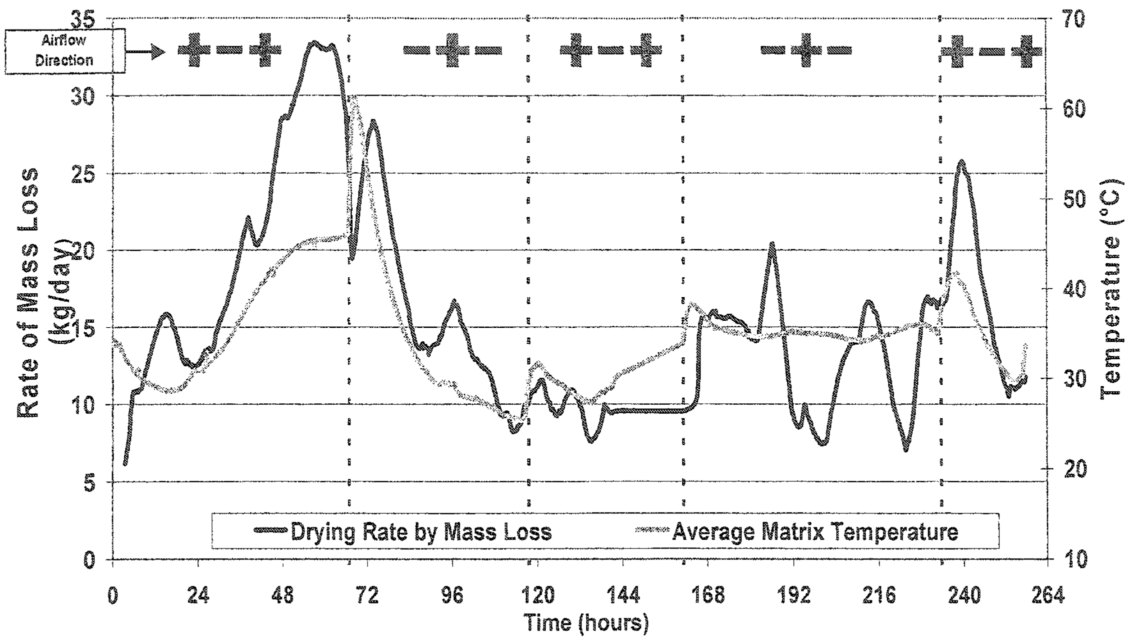

Figure 7.7: Average Internal Matrix Temperature Comparison with Rate of Drying - Experiment 1

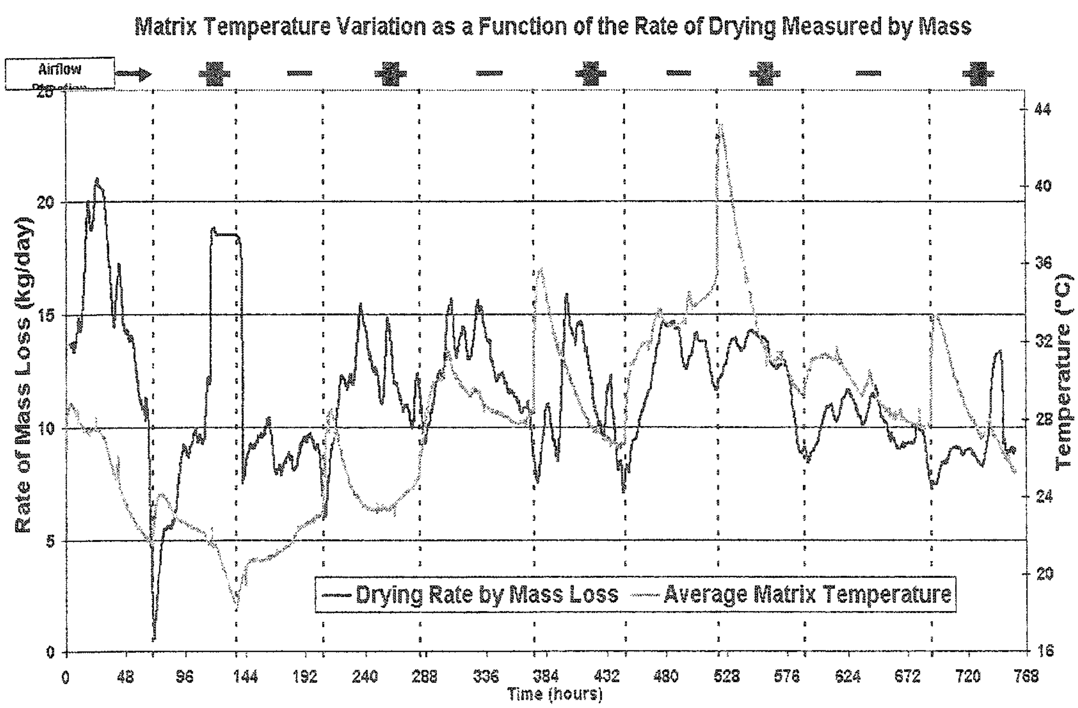

Figure 7.8: Average Internal Matrix Temperature Comparison with Rate of Drying - Experiment 3

Table 7.3 summarizes the drying performance of all three experiments including the overall mass reductions for both water and carbon on an absolute and daily basis. The second experiment displayed the highest rates of water and carbon removal at 15.4 kg/day and 2.62 kg/day respectively. It also maintained the highest average internal temperature at nearly 43°C, peaking to nearly 65°C. Given that the internal matrix temperatures and carbon losses for experiments 1 and 3 were lower than in experiment 2 (see Figure 7.9), it is quite clear that high metabolic activity leads to a more efficient drying system, however this efficiency must be balanced against increased carbon losses that reduce the calorific value of the dried product. Table 7.3 shows solid mass losses (assumed to be carbon losses) of between 5% and 18%. While no ultimate elemental analysis was done, based on literature data (summarized in Table 2.1, Section 2.2), sludge and woodwaste contains approximately 50% carbon. The measured dry mass loss would therefore translate into a 10% to 38% carbon loss. However, the carbon is complexed with other elements, so only elemental analysis of samples before and after biodrying would yield true carbon losses.

Table 7.3: Summary of Key Results for Each Experiment

	Experiment #1	Experiment #2	Experiment #3
Overall Run Duration	11 d	13 d	32 d
Original Solids Content	252 kg	187 kg	190 kg
Estimated Carbon Loss	14 kg (5.5%)	34 kg (18%)	16 kg (8.4%)
Original Moisture Content	280 kg	424 kg	588 kg
Estimated Moisture Loss	150 kg (53.5%)	200 kg (47%)	347 kg (59%)
Average Moisture Loss Rate	13.6 kg/d	15.4 kg/d	10.8 kg/d
Average Matrix Temperature	34.9 °C	42.7 °C	27.5 °C

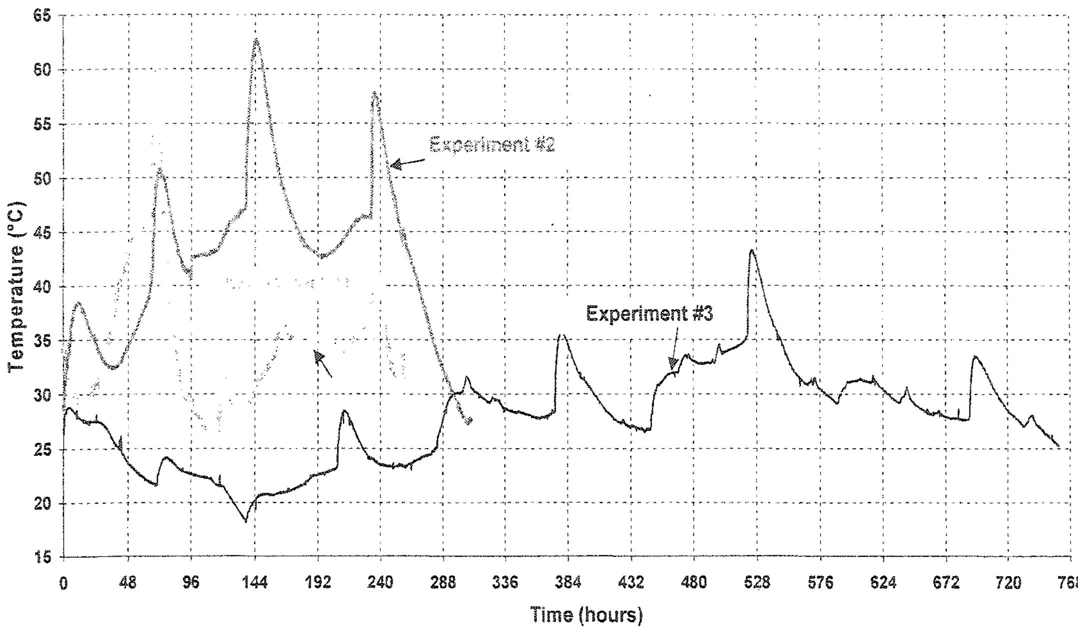

Figure 7.9: Average Internal Matrix Temperature for All Experiments

7.2.3 Matrix Dryness Uniformity

Once each experiment was concluded, 6 samples were removed at each of three reactor heights (10, 30, and 50 cm from the bottom), mixed, and moisture measurements made to determine whether the batchwise experiments had achieved a uniformly dry matrix. Samples were taken in a grid pattern taking into account all sections of the reactor. Table 7.4 summarizes the matrix %solids sample data from the three experiments. There was little to no variation in dryness along the aeration conduit axis (front to back). The matrix had dried quite uniformly from top to bottom, however was slightly drier at the bottom in all three experiments. This could indicate that the matrix near the reactor bottom dries preferentially due to a lower resistance to air flow (the shortest distance between the air ports).

Table 7.4: Solids (%) in Samples Taken From the Reactor at Different Heights

EXPERIMENT		#1	#2	#3
Initial Composite	(3 samples)	47.4%	30.5%	24.5%
50 cm from bottom	(6 samples)	60.5%	41.2%	28.8%
30 cm from bottom	(6 samples)	65.4%	41.6%	34.3%
10 cm from bottom	(6 samples)	*65.6%*	*44.5%*	*42.0%*
Final Composite	(3 samples)	65.7%	41.6%	40.5%

7.2.4 Matrix Pneumatic Characteristics

The pneumatic performance of the biodrying reactor is critical for good system control and uniform air distribution throughout the matrix. Figure 7.10 depicts the flow patterns followed by air streams in a system of uniform material porosity and permeability (material assumed to be isotropic for these flow patterns). The grey circles indicate points of pressure measurement. These were positioned in the reactor to provide as uniform a pressure profile as possible. The key pressure measurements are located between the aeration conduits, while those above the conduits serve as indicators of short-circuiting (flow going straight up). As, it was assumed that there was no flow in the z-direction most of the measurement points were along the center of the reactor (perpendicular to the aeration conduits). Manual pressure measurements were taken along the z-direction to confirm that there was indeed was no flow in this plane. There were 3 vertical pressure points located between the aeration plenums, on Probes A and B at heights of 10 cm (towards the front of the reactor), 30 cm (at the center of the reactor), and 50 cm (toward the back of the reactor). Pressure readings mirrored one another on the "A" and "B" side of the reactor (on either side of the center conduit). This fact, when coupled with the uniform dryness samples taken at the end of the experiment (see Section 7.2.3) confirms the negligible z-direction airflow. The flow patterns shown in Figure 7.10 are for the "+ – +"flow configuration. It can be seen that the center conduit acts to attract air and moisture to it, rather than being lost out the top of the biomass matrix.

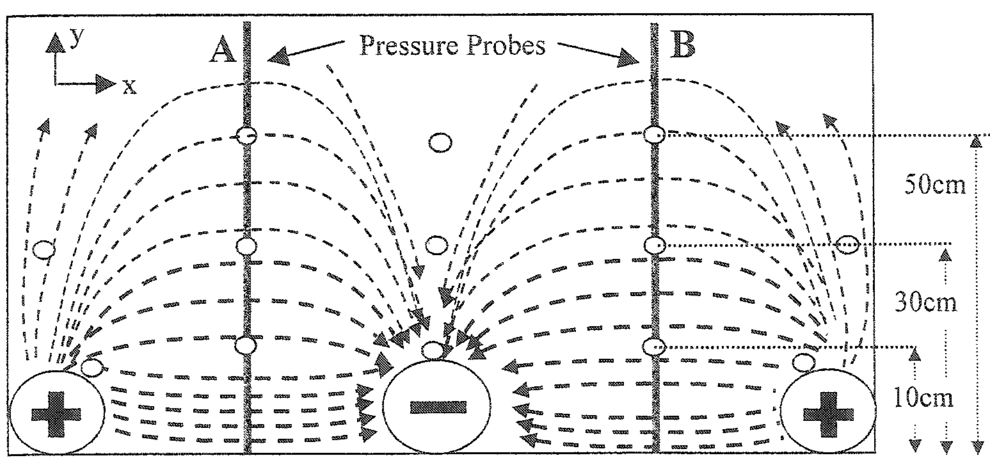

Figure 7.10: Flow Line Pattern in the "+ - +" Configuration

Darcy's Law describes flow in porous media:

$$\vec{V} = -\frac{K}{\mu}\nabla p \tag{7.6}$$

where $\vec{V}$ is the fluid velocity (air), μ is the fluid viscosity, **K** is the permeability of the porous material, and ***p*** is the pressure. Darcy states that for laminar flow in a porous media, the fluid flow is proportional to the pressure drop and inversely proportional to the fluid viscosity and the linear distance traveled. In these experiments, the pressure drop was calculated between the aeration conduits and the center probes. The primary direction of flow is therefore in the x-direction, and was considered to be dominant over the y-direction flow. Therefore, if the flow between two points is considered one-dimensional, an acceptable approximation of the pressure drop is the following:

$$\nabla p \approx \frac{dp}{dr} \tag{7.7}$$

where ***r*** is assumed to be a linear distance between the aeration source and the measurement point, allowing for *(7.6)* to be re-written as:

$$V = -\frac{K}{\mu}\frac{dp}{dr} \tag{7.8}$$

Darcy's Law was applied to elements for which the differential pressures were known within the biodrying reactor (see Figure 7.11). The mass flow of air through a given (rectangular) element (A_1, A_2, or A_3) was calculated using the following:

$$\dot{m} = \rho VA = \rho\left(-\frac{K}{\mu}\frac{dp}{dr}\right)A \tag{7.9}$$

where $\dot{m}$ is the mass flowrate in kg/s, ***ρ*** is the density of the fluid (air in kg/m^3), and **A** is the cross-sectional area traversed by the air. The area is represented as the rectangle that extends from the front of the reactor to the back for a distance of 10 cm above and below each pressure measurement point (see Figure 7.11).

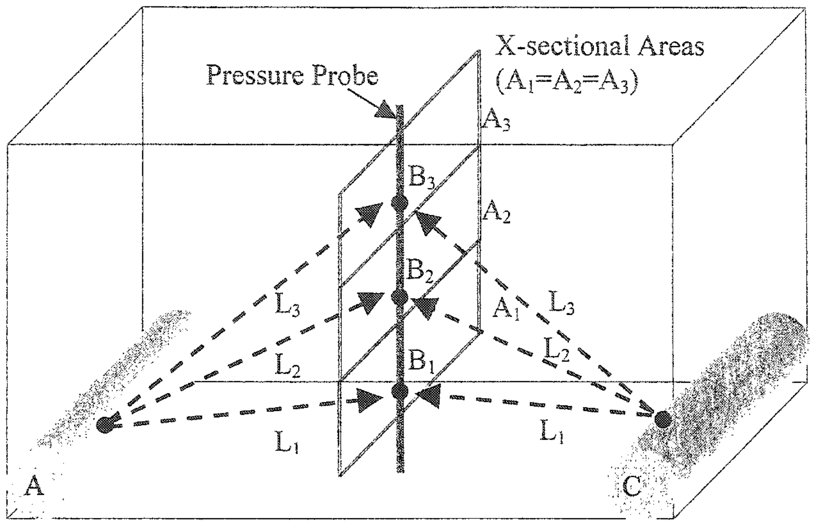

Figure 7.11: Schematic Describing Pressure Calculations

If equation *(7.9)* is applied to each of the ***i*** pressure measurement points it yields:

$$\dot{m}_i = \rho_i \left(-\frac{K}{\mu} \frac{dp}{dr_i} \right) A_i \qquad (7.10)$$

where the density ρ_i is calculated using the ideal gas law, employing the average pressure between the two pressure points, as follows:

$$\rho_i = \frac{(p_c + p_i)}{2RT_i} \qquad (7.11)$$

where **R** = the gas constant / molar mass of air (8,314 $m^3 \cdot Pa/kg\ mol \cdot K$ / 29 kg/kg mol = 287 $m^3 \cdot Pa/kg \cdot K$) and T_i is the temperature in degrees Kelvin. p_c is the pressure measured directly on the aeration conduit (not the pressure within). Laboratory testing (Jasmin, 2000) has shown that the pressure profile in the reactor varies in a logarithmic fashion across a radial distance ***r***, which yields:

$$p(r) - p_{atm} = \frac{(p_i + p_c)}{\ln(L_i)} \ln(r) + p_c \qquad (7.12)$$

where L_i is the actual distance in the reactor between two points of element *i* (see Figure 7.10). Taking the derivative:

$$\frac{dp}{dr} = \frac{(p_i + p_c)}{\ln(L_i)} \frac{1}{r} \tag{7.13}$$

and substituting (7.13) into (7.10) gives the following:

$$\dot{m} = K_e \sum_{i=1}^{3} \left[\frac{\left(p_i^{\,2} - p_c^{\,2}\right)}{2RT_i \ln(L_i)} \frac{A_i}{L_i} \right] \cong \dot{m} = K_e \cdot F_A \tag{7.14}$$

where $\boldsymbol{K_e}$ is the effective permeability of the material, equal to the permeability, K, in [m^2], divided by the viscosity of air, μ ,in [Pa·s], and $\boldsymbol{F_A}$ is the lumped summation term. The units of Equation *7.14* are as follows:

$$\dot{m}\left[\frac{kg}{s}\right] = K_e \left[\frac{m^2}{Pa \cdot s}\right] \cdot F_A \left[\frac{kg \cdot Pa}{m^2}\right] \tag{7.15}$$

$\mathbf{F}_A$ represents the force required to move given mass of air through an isotropic material. The parameter F_A is plotted versus time in Figure 7.12. Figure 7.12(A) represents F_A between the center conduit and pressure measurements on Probe A, while Figure 7.12(B) is calculated between the side conduits and Probe A (see Figure 7.10).

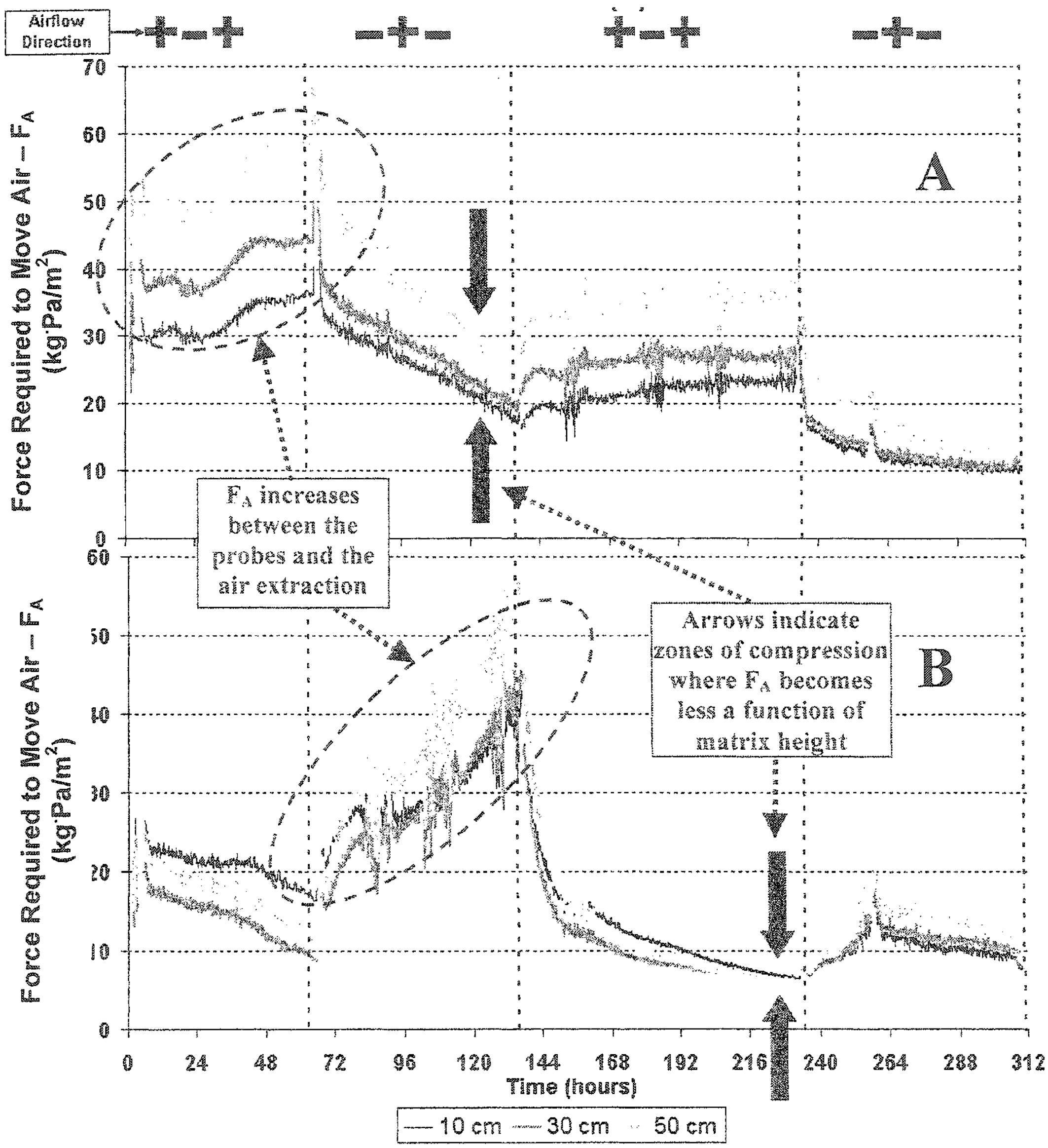

Figure 7.12: Calculated Aeration Forces (A) Center Conduit to Probe, (B) Side Conduit to Probe - Experiment 2

On the forced air side of Probe A [periods "– + –" for 7.12(A) and periods "+ – +" for 7.12(B)], the following can be observed:

- the force initially required to move air is larger for the points higher in the matrix where L is greatest
- F_A decreases significantly with time as the matrix becomes drier between the air entry point and the probe
- as the matrix becomes uniformly drier and permeability improves, F_A becomes less a function of matrix height (note the arrows in Figure 7.12)
- in the last period when the matrix is the driest, the rate of change of F_A is minimum

On the air extraction side of Probe A [periods "+ – +" for 7.12(A) and periods "– + –" for 7.12(B)], the following can be observed:

- F_A increases with time
- the greatest rate of increase with time is during the second period when the sludge is still wet, and there is the greatest potential for rewetting of dried sludge on the extraction side of Probe A

From equation *(7.15)* and the viscosity (μ) of air, the matrix permeability **K** can be calculated as follows:

$$K = \frac{\dot{m} \cdot \mu}{F_A} \tag{7.16}$$

It should be noted that the permeability, K is only applicable in an isotropic medium. For the purposes of these calculations, it was assumed that the biomass matrix had uniform permeability between the points measured (between conduits). Figure 7.13 shows matrix permeability versus time, and is meant to show overall trends, as detailed permeability calculations would require more elaborate experimental set-ups. The permeability increases significantly during forced (injected) air periods, as drying progresses, and conversely the permeability decreases during extracted air periods as the sludge was rewetting. This phenomena is due the fact that under positive aeration, the moisture gradient moved away from the conduit, carrying water away and leaving void spaces filled with air, increasing the permeability.

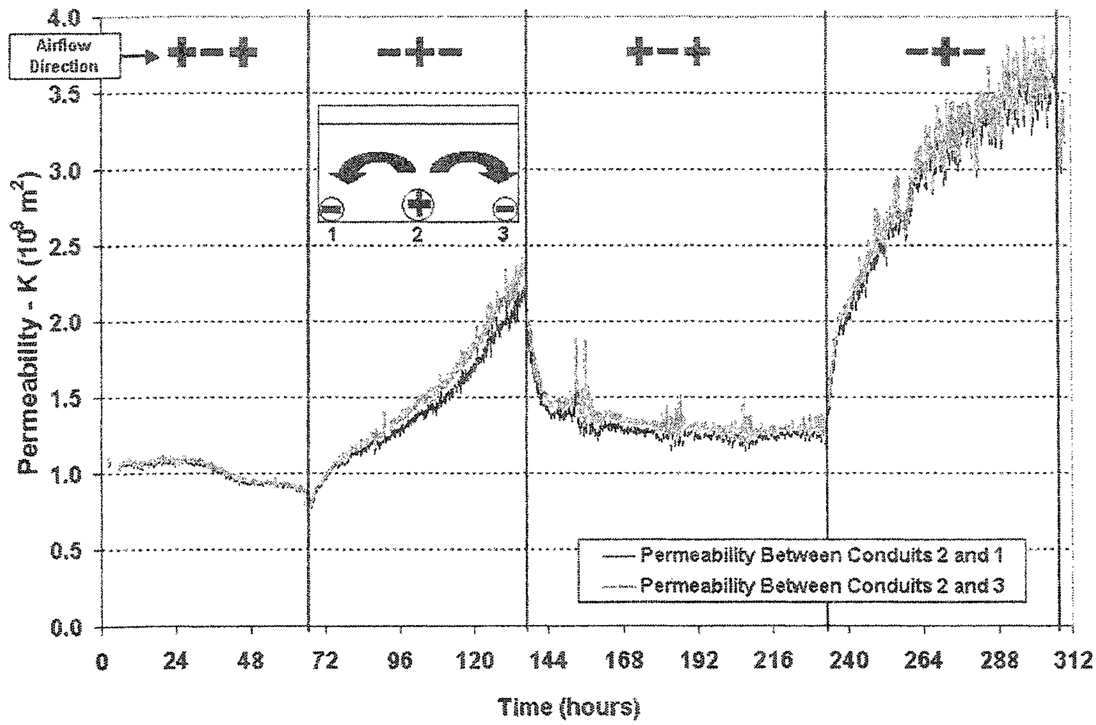

Figure 7.13: Permeability of the Biomass Matrix - Experiment 2

7.3 – Discussion

In summary, the experimental results indicate the following:

- mass balances for carbon and moisture around the biodrying reactor have been closed with a high level of certainty
- moist air rewets dried sludge when air flow is reversed, resulting in renewed biological activity and increased matrix temperatures for a period of 10-20 hours
- the rewetting period and increased biological activity is accompanied by an increased rate of carbon loss from the matrix

- the matrix rewetting is most significant in the earlier periods of the batch experiments when the overall matrix is still quite wet
- higher matrix and outlet air temperature permits saturated air to carry more moisture on a mass basis, thus increasing the rate of drying
- the outlet air is saturated once the matrix temperature rises above a threshold, about 40°C in the case of experiment number 2
- there are indications that air flow preferentially passes via the shortest route between the inlet and outlet air ports, preferentially drying the lower matrix
- as the matrix dries, the permeability of the matrix increases dramatically, lowering the pressure loss across the matrix and reducing the extent of preferential flow in the lower reactor
- the second experiment (1:0.5 sludge to woodwaste ratio) displayed improved performance, however this was likely due to particularly favourable sludge characteristics for that experiment (fluffy, low secondary content)

These observations lead to several conclusions that may result in improved process performance of the batch system, as follows:

- there is good opportunity to use higher air flows than in these experiments (while still maintaining higher temperatures and acceptable pneumatic conditions), which could reduce sludge treatment time
- temperature spikes were noted after each periodical change in air flow direction (likely due to a rewetting of dry sludge), and there was a clear relationship between high matrix temperatures and rates of drying. This observation indicates that increased overall rates of drying might be achieved if air switching occurs more frequently (say every 10 hours or so) to maintain higher matrix and outlet air temperatures
- it was found that there was more air passage in the lower portions of the batch reactor configuration than near the top (especially in the early stages of the batch treatment). This

observation implies that higher efficiencies and drying rates might be achieved with a new continuous reactor configuration, whose concept is described below

7.3.1 New Continuous Reactor Concept

In order to maintain uniform sludge treatment and to avoid preferential matrix drying, a new continuous biodrying reactor concept is proposed as illustrated in Figure 7.14. Sludge would be deposited on the top of the reactor, and slowly fall to the reactor bottom, being dried by cross-flow air as it falls. The continuous reactor would be taller than the batch system, thereby favouring installation in crowded mill sites because of its smaller layout. The biomass filling and discharging technology would be similar to that employed at pulp and paper mills for bark handling.

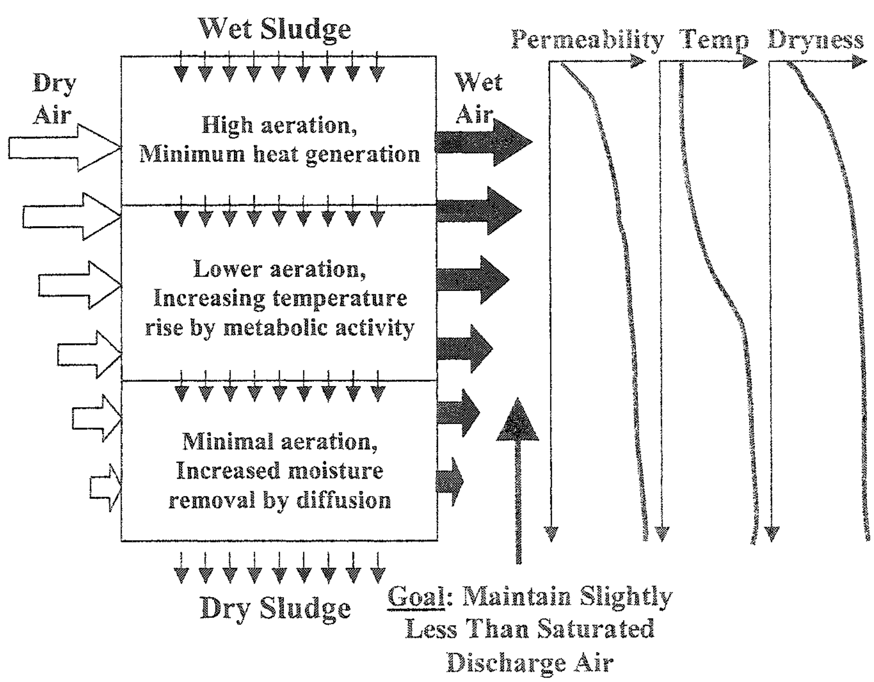

Figure 7.14: Continuous Biodrying Reactor Concept

Air would be supplied at different flow rates down the reactor, controlled by the air outlet relative humidity (to be maintained at slightly less than 100%). The reactor profiles for matrix permeability, temperature and dryness are expected to be as shown in Figure 7.14. Higher air flow rates in the upper reactor will convey surface moisture from the sludge matrix at a high rate, maintaining a lower sludge temperature and thereby preserving the higher heating value of the sludge. As the surface water is eliminated, the controlled airflow will reduce, as moisture removal will be limited by diffusion from inside the matrix elements. At this point, provided that there is still adequate moisture and/or nutrients to permit good biological activity, airflow will reduce and the matrix temperature should rise thus accelerating moisture release from inside the matrix elements.

7.4 – Conclusions

A biological sludge drying reactor was investigated experimentally. Good rates of water removal were achieved for different mixture of paper mill sludge and woodwaste. Pneumatic performance within the matrix was well defined and allowed for meaningful observations. These observations lead to several conclusions that may result in improved process performance of the batch system, as follows:

- there is good opportunity to initially use higher air flows than in these experiments (while still maintaining acceptable pneumatic conditions), which could reduce sludge treatment time
- temperature spikes were noted after each periodical change in air flow direction (likely due to a rewetting of dry sludge), and there was a clear relationship between high matrix temperatures and rates of drying. This observation indicates that increased overall rates of drying might be achieved if air switching occurs more frequently (say every 10 hours or so) to maintain higher matrix and outlet air temperatures

When considering the mechanisms of moisture removal and material handling, a proposed vertical continuous reactor with tapered aeration rates could yield improved drying performance and integration into existing mill systems.

8.0 – TECHNO-ECONOMIC EVALUATION OF THE BIODRYING PROCESS

It should be noted that some material in this section is contained in a manuscript that will be submitted to the peer-reviewed TAPPI Journal (see Appendix II).

8.1 - Description of Novel Biodrying System

This section presents the results of a techno-economic study in which the performance of the biodrying process was simulated, and the capital and operating costs for the installed process were estimated. Figure 8.1 shows how the biodrying system would be incorporated in a simplified AST process (from Figure 2.1). In the process concept investigated, mixed dewatered sludge produced by the mill effluent treatment facilities is combined with bark as a bulking agent and then fed to the biodrying process where sludge drying rates are enhanced by the exothermic metabolic activity of aerobic thermophilic microorganisms. After drying, the sludge is removed and sent for combustion in a biomass or hogfuel boiler.

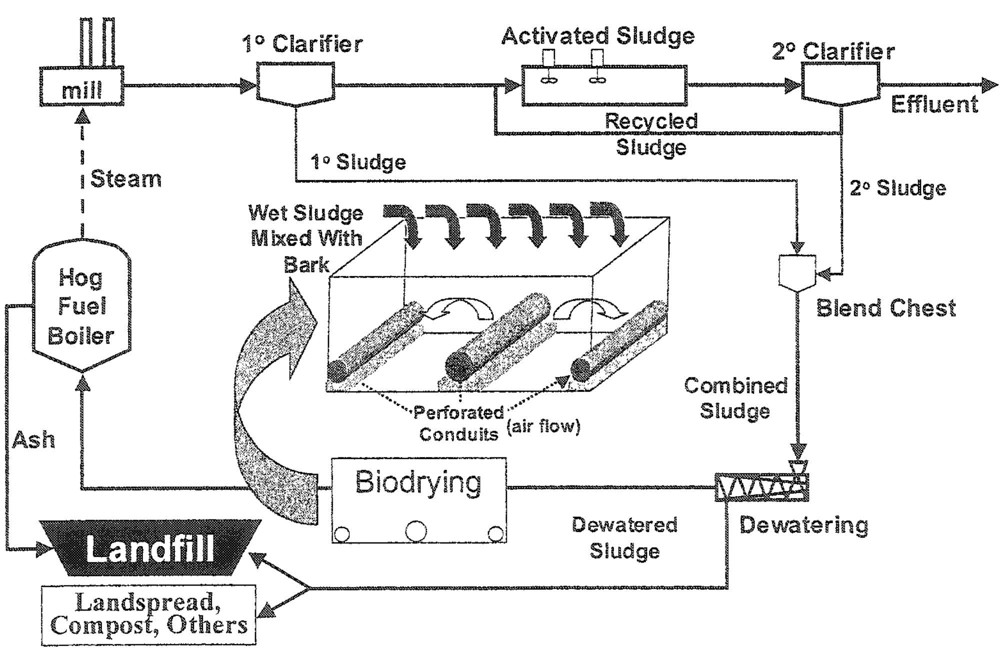

Figure 8.1: Biodrying Process Integrated into Activated Sludge Treatment Facilities

The batchwise biodrying reactor depicted in Figure 8.1 is further detailed schematically in Figure 8.2. Biodrying essentially acts as an accelerated composting process, controlled through a system of aeration conduits, and housed in a reactor structure that restricts airflow within the biomass matrix and facilitates its material handling.

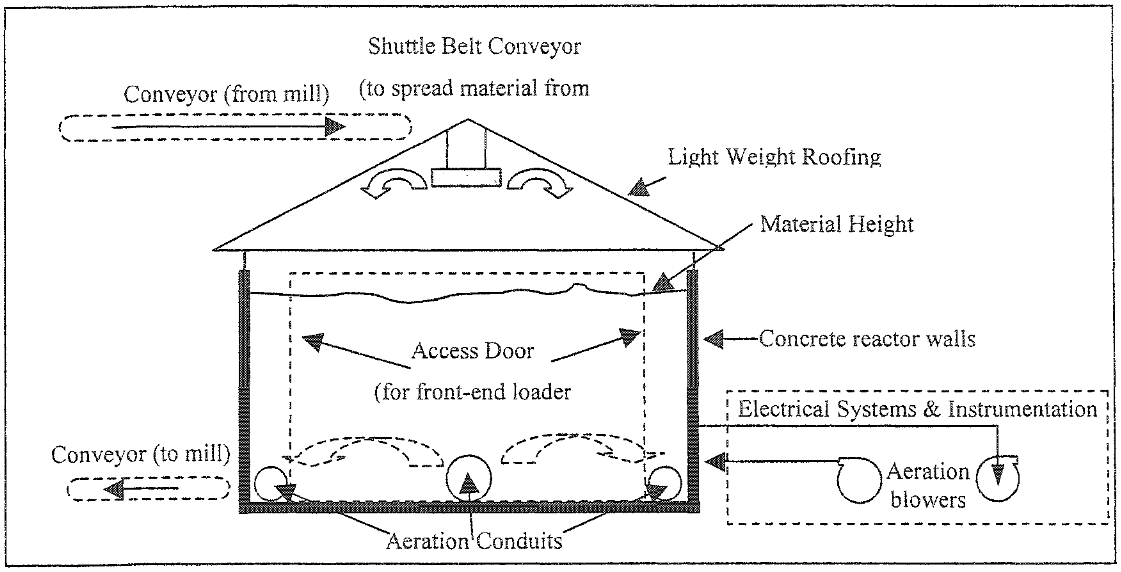

Figure 8.2: Biodrying Process Schematic

The reactor is sized in order to accommodate the volume of the sludge and woodwaste mixture for an appropriate residence time to ensure drying (between 3-14 days). The height and width of the unit remain constant (7m x 18m), while the length can be modified, as there is little drying variation in this direction (see Section 7.2.3). As this is a batch setup, a minimum of two reactors would be required so that one could be filled/emptied while the other is in the drying mode. Reinforced concrete is the material of construction used here; however, steel is another option. For the purposes of this design, the mixing of sludge and woodwaste is accomplished using existing mill facilities (variable speed conveyors) and the mixture is then transported a short distance (100 m) to fill the reactors. There the material is applied from the top via a shuttle belt conveyor suspended from the roof of the system (this roof is required to keep precipitation out, but does not have to be sealed). Material is removed after the allotted drying time (~7 days) by opening one side of the reactor and using a front-end loader. Three parallel aeration conduits run along the bottom of the reactor, operating in either the positive (air injection) or negative (air extraction) configurations. These conduits are perforated so that an equal aeration is applied along the length of the aeration plenums. Each reactor is equipped with two blowers (one for air injection and one for air extraction) that pipe air to and from the conduits. The piping system (12" SS) also contains the necessary airflow instrumentation (i.e., flow, temperature, pressure, and relative humidity probes) for aeration control and monitoring. The air extracted from this system would primarily be wet air with possible particulate and odours in the case of anaerobic conditions. The biodrying exhaust air could be treated using the mill's existing air handling system where applicable; being used as primary or secondary air in the boilers. If this option were not possible, exhaust air would first be treated for particulate and monitored for VOC's and anaerobic gases (CH_4, H_2S, etc.).

8.2 - Objectives

The objective of this techno-economic study was to interpret the results obtained from bench-scale testing of the novel biodrying process presented in this thesis. This performance data was used to evaluate the capital and operating costs associated with a full-scale biodrying process installed in a target mill scenario. The capital and operating costs at various other mill scenarios were subsequently analyzed in order to characterize and identify mills for which this process would be economically attractive.

8.3 - Techno-Economic Analysis Methodology

Figure 8.3 summarizes the study methodology. A base case mill was defined from an actual integrated pulp and paper installation, and the capital and operating costs of the biodrying process were calculated based on performance data obtained from the laboratory experiments from Section 7. Following this, a sensitivity analysis of parameters in the base case was performed to determine which factors had the greatest effect on the simple payback period. Finally, using this knowledge about critical parameters, various hypothetical but realistic mill scenarios were defined and payback periods were calculated for these mills. The goal here was to identify broad trends in the operation parameters of such a technology. A full-scale characterization has not yet been performed related to the laboratory experiments, so assumptions were made herein.

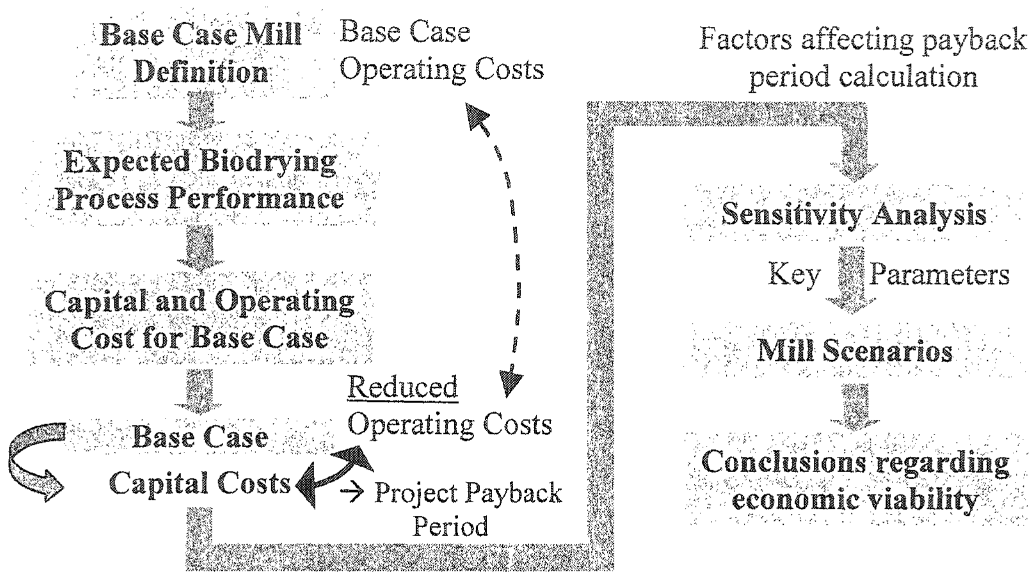

Figure 8.3: Summary of Techno-Economic Study Methodology

8.3.1 Capital Costs for Biodrying System

The full-scale biodrying system is based on the dimensions and shape of the laboratory unit. It was assumed that multiple batch reactors would be required to meet the material flow of a mill. It is assumed that the reactors would be installed on level ground within or near the mill complex. The reactors would be placed next to one another, sharing communal systems such as drainage, site access, and electrical substations. While quotes were assembled for the blowers as well as for the instrumentation and material handling systems, the rest of the system was assumed to be fabricated. Unit costs were used for concrete, piping and structures. With the width and height of the reactors fixed, the length was varied in order to adjust the volume of the system. However, the maximum reactor length was set at 35 m, in order to avoid problems inherent to very large systems. These difficulties include the logistics of reactor emptying, and the maintenance of sufficient conduit pressure, which would necessitate extremely large blowers, entailing high capital costs and electrical requirements. Indirect cost factors were applied to the capital cost items and finally a 10% contingency was added.

Table 8.1 summarizes some of the primary biodrying system costs. The largest cost items in the biodrying process include the reactors (primarily concrete and structural steel roofing), the material handling equipment (conveyors, mixers, and loaders) and the air blowers (including motors and electrical sub-systems).

Table 8.1: Capital Cost Estimate Systems Considered Within Process Battery Limits

Biodrying Reactor	reinforced concrete structure, site drainage, aeration conduits, roofing, access hatch, stairwells, lighting, platforms.
Blowers & Piping	pressure and vacuum blowers, piping, valves, air/water separator, electrical systems (MCC, sub-stations)
Material Handling	bark shredder assembly, belt conveyors, shuttle belt conveyor, electrical systems, traveling screw reclaimer, front end loader
Instrumentation & Control	sensors (rH, T, Q, P), data acquisition hardware and software
Indirect Capital Costs*	detailed engineering (7%), contractor (4%), construction management (3%), start-up (1%), contingency (10%)

* indirect costs based on consultation with Jacques Perignon of AMEC Engineering, 2003.

8.3.2 Operating Costs and Savings for Biodrying System

The operating costs and general assumptions for this study are elaborated below:

Fossil Fuel: In most biomass power boilers, some supplemental fossil fuel is required. Fossil fuels raise temperatures in the combustion zone and improve boiler efficiency. Without biodrying, a pulp and paper mill burns combinations of sludge, woodwaste, and fossil fuels to achieve the target energy production in gigajoules (GJ). With the implementation of the biodrying process, it is assumed that a reduction in fossil fuel requirements will be achieved.

Woodwaste: Woodwaste is a bulking agent for the biodrying process. It has been assumed that once biodrying is installed, woodwaste that is not used as a bulking agent continues to be used as boiler feed material together with the dried biodrying product.

Sludge Disposal: The sludge disposal cost without biodrying includes the cost associated with removing sludge from the mill site by either landfilling or landspreading operations. Ash disposal from the mill boilers is a continued cost, and is included because increased sludge combustion results in higher ash production.

Electricity: The primary operating cost for the biodrying process is the electrical power required to run the aeration blower motors.

Material Handling: Mechanical conveyors are required to transport material to and from the biodrying reactors. These are enclosed, belt type conveyors that are typically used in cold weather regions. It is assumed that the tie-in points to the existing process would be at the sludge/woodwaste mixing facilities (used in preparing biomass fuel for the hog boiler). These facilities would mix sludge and woodwaste in the ratios needed for the biodrying process, with any excess woodwaste being sent directly to the boiler. The goal is to maintain a constant sludge feed to the biodrying reactors, eliminating stagnant sludge piles to avoid odour potential. If the reactor is emptied manually using front-end loaders, the operating costs reflect fuel and manpower requirements. It is assumed that conveyors are used to bring sludge to the reactors, since they must feed the overhanging shuttle belt conveyor (too high to be reached by loaders). Emptying is accomplished with loaders and the material is brought to existing biomass holding areas, which are used to maintain a steady feed to the biomass boilers.

Labour: In addition to the manpower required for front-end loader operation, one full-time biodrying operator has been assumed. This person would control sludge/woodwaste mixing ratios, aeration rates, and logistics.

Greenhouse Gas Mitigation: The impact on the atmosphere due to releasing greenhouse gases is normally expressed by the emission of carbon dioxide equivalents (CO_{2E}). For instance, methane (CH_4) as a greenhouse gas is 21 times more harmful than CO_2 (Galle et al., 2001). Legislation is not yet in place, but eventually it is expected that industry will operate on a credit system where GHG emission certificates will be purchased from the government or on the open market. One possible scenario is that 85% of a mill GHG emission would be free, and the remaining 15% would be purchased at between \$10 and \$50 per tonne of CO_{2E} (Browne, 2003). A \$10 per tonne of CO_{2E} assumption is used in this study.

The model uses the current sludge generation and disposal practices at the mill. This assumes a set production rate of sludge at a given moisture content. For the most part, this sludge (@ ~ 20 - 35% dryness) is mixed with purchased bark (@ ~ 50 - 60% dryness) with the goal of increasing the bulk solids content of the material as high as possible. The mixture, usually containing 2 - 3 times as much bark as sludge, is then sent for combustion in the mill's biomass boiler. The total energy value for the mill is evaluated based on sludge and woodwaste energy values, as well as average fossil fuel consumption (used to supplement burning). From this value, a pre-biodrying feed energy is calculated, with the goal being to supply an equal amount of energy to the boiler once biodrying is included. The dried biomass augments the energy being sent to the boiler, allowing for reductions in fossil fuel consumption and thus in operating costs. When sludge characteristics or bark delivery problems impede the mixing of sludge into the boiler feed, the sludge is shunted to landfill or an alternate disposal method. In mills where sludge was never mixed into the biomass boiler's feed, pre-biodrying energy calculations were based only on bark and fossil fuel usage.

The biodrying system is sized to accommodate all the sludge produced from the wastewater treatment operations, with bark added only as a bulking agent to improve airflow in the reactor matrix. Since this requires less bark than in the pre-biodrying configuration, the remaining bark is sent directly for combustion. Now, with fossil fuel demand and sludge disposal lowered or eliminated, the operating costs are recalculated.

The primary benefits due to the implementation of the biodrying process at a pulp and paper mill in the techno-economic study include the following:

Fossil Fuel Savings: The dried sludge has an augmented caloric value that reduces the need for supplemental fuel (natural gas, bunker, etc.) in the boiler. Fossil fuel is often required in combustion boilers to stabilize their operation, especially when excessively wet sludge is being fired. Dry biomass is far less expensive as a fuel source, is readily available on-site, and is less subject to price fluctuations.

Reduction in Landfilling/Landspreading Practices: Reduced or eliminated sludge disposal costs can be realized due to sludge being combusted on-site, and this also eliminates uncertainty associated with ongoing landfill and landspreading practices. Savings can be realized in both sludge transport and tipping fees/disposal.

Greenhouse Gas (GHG) Emissions Reduction: Under the Kyoto Protocol, biomass combustion is considered as net-zero for CO_2 emissions. Therefore the future value of GHG credits will create a financial incentive for projects involving increased biomass combustion and decreased fossil fuel usage, such as is the case with the proposed biodrying process.

8.4 - Techno-Economic Base Case Model

A detailed base case analysis was made of an 1800 TPD integrated pulp mill located in northwestern Quebec. This mill produces 100 dry tonnes of wastewater sludge per day at 26% dryness on average. Typically, 16% of the sludge is sent to landfill with the remaining 84% being burned in an existing woodwaste furnace. This sludge is currently mixed in a 1:3.5 ratio with woodwaste (~ 300 dry tonnes per day of sludge/woodwaste) and fed into the power boiler. The power boiler is supplemented with 22,000 m^3/day of natural gas, averaged over a yearly basis.

The model input parameters are separated into seven categories in Table 8.2: sludge, disposal, woodwaste, energy, biodrying, GHG, and material handling. The input parameters used in the techno-economic model of the biodrying process are summarized according to the following:

- base case mill parameter values
- ranges of parameter values used in the sensitivity analysis

Most of the variables in Table 8.2 describe material characteristics (masses, dryness, energy content, etc.) and energy costs and penalties (e.g. greenhouse gas numbers). The parameters that have the greatest effect on the process are the biodrying ones. These relate back to the laboratory results from Section 7. The target dryness for biodrying is fixed at 50%, although some scenarios will involve other dryness values. The residence time chosen for the base case (7 days) is lower than what was achieved with the preliminary batch tests (10, 13, and 30 days for the 3 experiments), but it is assumed that with proper optimization, faster residence times are possible. The average internal temperature achieved within the matrix is slightly higher in the base case (50°C) than in the experiments (~35°C, ~43°C, and ~28°C). However, the lower temperatures obtained during the bench-scale tests were caused by small sludge volumes (1 m^3), where the percentage of material close to the walls (a heat sink) is much higher than in a full-scale system. Finally, carbon loss is assumed to be 10% of the feed mass of dry solids. Carbon losses in the laboratory varied considerably, from about 3% to 20%. The phenomenon of carbon loss requires more investigation, but there was a moderate correlation between high internal temperature and increased carbon losses (as in Run #2). Therefore, in order to investigate the effect of biological activity on system economics, it was assumed that carbon losses were linked to internal average temperature. The mixing ratio that gave the best results from the laboratory was a mixture of 1 part sludge to 0.5 parts bark, on a dry basis. This then is used as the base case for full-scale operation. The composition of feed material will always be changing, so in reality the ratios would constantly need to be monitored to ensure good biodrying performance and that the material handling systems can effectively convey the mixture. It is clear that increased proportions of bark will increase the overall system volume, so only the minimum amount of woodwaste required would be used in the biodrying reactors.

Table 8.2: Base Case Parameters and Sensitivity Analysis Ranges Supplied to the Techno-Economic Model of the Biodrying Process

Parameter	*Base Case*	*Range*	*Comments*
SLUDGE PARAMETERS			
Sludge Production [t/d]	100	100[a]	dry tonnes / day
Sludge Dryness out of Dewatering [%]	26%	20-40[a]	≅ biodrying feed
Sludge Density out of Dewatering [kg/m^3]	700	500-1000	
Energy Content of Sludge [GJ/t]	18	16 – 24[b]	higher heating value, HHV
Ash Percentage of Sludge [%]	10%	0 – 20%[b]	ash ≅ no energy value
DISPOSAL PARAMETERS			
Percentage of Sludge Sent to Landfill [%]	16%	0 – 100%	% sent before biodrying
Percentage of Sludge Sent to Landspread [%]	0%	0 – 100%	" "
Cost to Landfill [$/dry t]	$30	$15 - $40[c]	incl. transport & tipping
Cost to Landspread [$/dry t]	$25	$10 - $30[c]	incl. transport & tipping
WOODWASTE PARAMETERS			
Woodwaste Usage for Combustion [t/d]	300	300[a]	dry tonnes / day
Woodwaste Dryness [%]	50%	45%-75%[b]	
Density of Woodwaste [kg/m^3]	400	400	
Energy Content of Woodwaste [GJ/t]	16	14 – 24[b]	HHV per dry tonne
Ash Percentage of Woodwaste [%]	5%	5%[b]	ash ≅ no energy value
Cost of Woodwaste [$/t]	$13	$13[a]	per dry tonne delivered
Combustion Sludge to Woodwaste Ratio [:]	1:3.5	1:3.5	ratio <u>before</u> biodrying
ENERGY PARAMETERS			
Natural Gas Consumed per day [m^3/day]	22,000	22,000[a]	yearly average
Cost for Natural Gas[$/m^3]	$0.42	0.40-0.70[a,d]	
Electricity Cost [$/kWhr]	$0.039	0.039-0.06[a,e]	
BIODRYING PARAMETERS			
Product Dryness <u>Out</u> of Biodrying [%]	50%	40% – 65%	set target value
Sludge to Woodwaste Ratio for Biodrying [:]	1:0.5	1:0 – 1:2	for bulking and porosity
Biodrying Residence Time [days]	7	3 – 14	time required to reach outlet dryness target
Ambient (Biodrying Feed) Temperature [°C]	20°	0° - 30°	injected air temperature
Ambient (Biodrying Feed) rH [%]	25%	10 – 75	injected air humidity
Average Matrix Temperature [°C]	50°	30° – 75°	≅ biodrying outlet T
Carbon Lost from Start of Biodrying Cycle to the End, [% of inlet dry solids]	10%	0% – 25%[f]	Caused by biological degradation
GREENHOUSE GAS PARAMETERS			
CO_2 from Burning Natural Gas [t/m^3]	0.002	0.002[g]	t CO_{2E} produced / m^3 gas
Methane Produced per Tonne Landfilled [t/t]	0.072	0.072[g]	
Cost of CO_2 [$/t CO_{2E}]	$10	$5 - $50[g]	15% of CO_2 production
CO_{2E} from Purchased Electricity [t/MWh]	0.05	0.05[g]	
MATERIAL HANDLING PARAMETERS			
Onsite Distances from mixing to biodrying [m]	100 m	10 – 500[a]	for conveyor costing

a: data supplied by mill
b: synthesized from: McBurney ('93); James and Kane ('91); Kraft and Orender ('93); Nickull et al.('91); La Fond et al.('97); Durai-Swamy et al.('91)
c: Scott et al. ('95)
d: National Energy Board of Canada (www.neb-one.gc.ca)
e: Hydro-Quebec 2002 Annual Report
f: Based on results from Section 7
g: Browne ['03]

8.4.1 Base Case Scenario Results

The base case scenario for the batch biodrying operation for 100 TPD of sludge is presented in Table 8.3. These are the results from the base case numbers provided in Table 8.2. The top half of the table compares operating costs with and without biodrying, whereas the system capital cost is summarized in the lower half of Table 8.3, including the direct payback period for the project.

The key assumptions for the base case capital and operating cost calculations include the following:

- the system defined in the base case assumes that a 1:0.5 mixture of sludge and bark is dried from 30% dryness to 50% dryness in 7 days
- the water removed from the sludge-woodwaste mixture increases its calorific value, which results in less fossil fuel being required in the power boiler to meet the same energy output as in the pre-biodrying case
- sludge landfilling costs are eliminated, with a small increase in ash landfilling due to the residual 16% of the sludge (that was landfilled prior to biodrying) that is now being combusted. The ash content of the sludge is 10%
- modest CO_2 credits are calculated, taking into account the reduced fossil fuel consumption assuming $10 per tonne of CO_2
- there is an increase in electrical consumption for the aeration blowers and mechanical conveyors
- the operation of a front-end loader for reactor emptying is required

An annual operating cost savings of more than $2 million is realized in the base case scenario. When the annual savings are balanced against the capital costs, the payback period for the base case is approximately two and a half years.

Table 8.3: Operating and Capital Costs for Base Case Project

DAILY OPERATING COST ITEMS	*Without Biodrying*	*With Biodrying*	*COMMENTS*
Cost of Woodwaste per Day (delivered to the mill)	$4,600	$4,600	no reduction ($13 per dry tonne)
Total Daily Fossil Fuel Costs	$9,240	$920	90% reduction from base case
TOTAL FUEL COSTS	$13,840	**$5,530**	
Biodrying Daily Electrical Cost	-	$1,620	2200 total hp for blowers
Material Handling Power		$44	60 total hp for material handling
TOTAL ELECTRICAL COSTS	-	**$1,665**	
Daily Landfilling Cost	$480	-	landfill eliminated
Daily Landspreading Cost	-	-	N/A
Daily Ash Disposal Cost	$700	$800	15% increase from base case
Manual Sludge Removal Costs	-	$880	8.8 front-end loader hours / day
TOTAL DISPOSAL COSTS	**$1,180**	**$1,680**	
Greenhouse Gas Production Costs	$79	$16	80% reduction from base case
DAILY TOTAL	**$15,100**	**$8,890**	
Yearly Total (365 days)	$5,512,000	$3,244,500	based on 365 days
Yearly savings from base case →	**A**	$2,267,500	
Yearly Operating Costs			
Maintenance	**B**	$141,830	3% of total installed cost
Operators:	**C**	$40,000	one @ $40,000 per year
Total yearly costs	**D**	$181,830	(**B** + **C**)
TOTAL ANNUAL SAVINGS →	**E**	$2,085,770	(**A** – **D**)
DIRECT COSTS			
Biodrying reactors		$ 1,300,700	(~25% of total capital cost)
Blowers & piping		$ 883,000	(~17% of total capital cost)
Material handling		$ 1,740,000	(~34% of total capital cost)
Instrumentation & control		$ 187,350	(~4% of total capital cost)
TOTAL DIRECT →		$ 4,111,050	
INDIRECT COSTS (%'age of Direct Costs)			
Engineering (7%), Construction (4%), Contractor (3%) Management, & Startup (1%)		$ 616,658	(~12% of total capital cost)
Contingency (10%)		$ 411,105	(~8% of total capital cost)
BIODRYING CAPITAL COST →		$ 5.14	million dollars
PAYBACK (years)		2.46	($5.14 divided by **E**)

8.4.2 Sensitivity Analysis of Critical Base Case Parameters

The base case represents conservative estimates and realistic performance numbers for the batch biodrying system based on bench-scale results. In order to see how changing various parameters would affect the payback period for this set of assumptions, a sensitivity analysis was performed.

For example, when considering just the biodrying residence time, the total system capital cost varied as follows:

3 days = \$3.40 million	9 days = \$6.55 million
5 days = \$4.77 million	12 days = \$7.07 million
7 days = \$5.14 million (base case)	14 days = \$8.52 million

The variations in capital cost were then compared with simulations where other parameters were varied similarly, and the relative impact was ascertained (High, Medium, and Low). A list of all the parameters that were varied in the sensitivity analysis is presented in Table 8.4. In addition to the total capital cost of the system, the performance outcomes considered for the process include: the annual savings incurred by implementing biodrying, the direct payback period, and the specific energy consumption (SEC) of the process. Table 8.4 summarizes the impact of each parameter on these outcomes, and ranks them in order of magnitude from highest to lowest.

It is important to mention that these parameters were varied individually, keeping the others fixed at base case values. The purpose of this parameter-by-parameter analysis is to identify which ones have the largest effect on the economics of the project. After this step, more realistic scenarios that combine multiple parameter variations are run through the model.

Table 8.4: Key Sensitivity Parameters and Their Relative Effect on Model Outputs

Sensitivity Analysis Parameter	***Yearly Savings***	***System Cost***	***Payback***	***Specific Energy***
Sludge Dryness From Dewatering	**HIGH**	**HIGH**	**HIGH**	**HIGH**
Biodrying Residence Time	**MED**	**HIGH**	**HIGH**	LOW
Woodwaste Dryness	**HIGH**	LOW	**HIGH**	LOW
Sludge to Woodwaste Ratio	LOW	**HIGH**	**MED**	**MED**
Average Matrix Temp. / C Loss	LOW	**MED**	LOW	**HIGH**
Conveyor Distances	LOW	**HIGH**	**MED**	LOW
Dryness out of Biodrying	**MED**	LOW	**MED**	**MED**
Tonnes of Sludge Treated	**MED**	**MED**	LOW	LOW
Cost for Natural Gas	**HIGH**	LOW	LOW	LOW
Percentage of Sludge Sent to Landfill	**MED**	LOW	LOW	LOW
Ambient (Biodrying Feed) Temperature	LOW	LOW	LOW	**MED**
Ambient (Biodrying Feed) rH	LOW	LOW	LOW	**MED**
Sludge Density	LOW	LOW	LOW	LOW
Cost to Landfill	LOW	LOW	LOW	LOW
Electricity Cost	LOW	LOW	LOW	LOW
Energy Content of Sludge	LOW	LOW	LOW	LOW
Ash Percentage of Sludge	LOW	LOW	LOW	LOW
Energy Content of Woodwaste	LOW	LOW	LOW	LOW
Cost of CO_2	LOW	LOW	LOW	LOW
Cost of Woodwaste	LOW	LOW	LOW	LOW

From Table 8.4, four key parameters were found to affect performance to the greatest degree: *feed dryness (sludge and woodwaste), biodrying residence time, sludge/woodwaste ratio, as well as the internal temperature maintained in the reactor throughout drying and the associated carbon loss.* Figures 8.4 A-D summarize the sensitivity analysis results for each of these key parameters. For these graphs, the black bars indicate the annual savings, the grey bars indicate the system capital cost, and the black line shows the direct payback in years. Note that values on the y-axis represent both the dollar amounts (in millions) and the number of years, as the two are similar in scale.

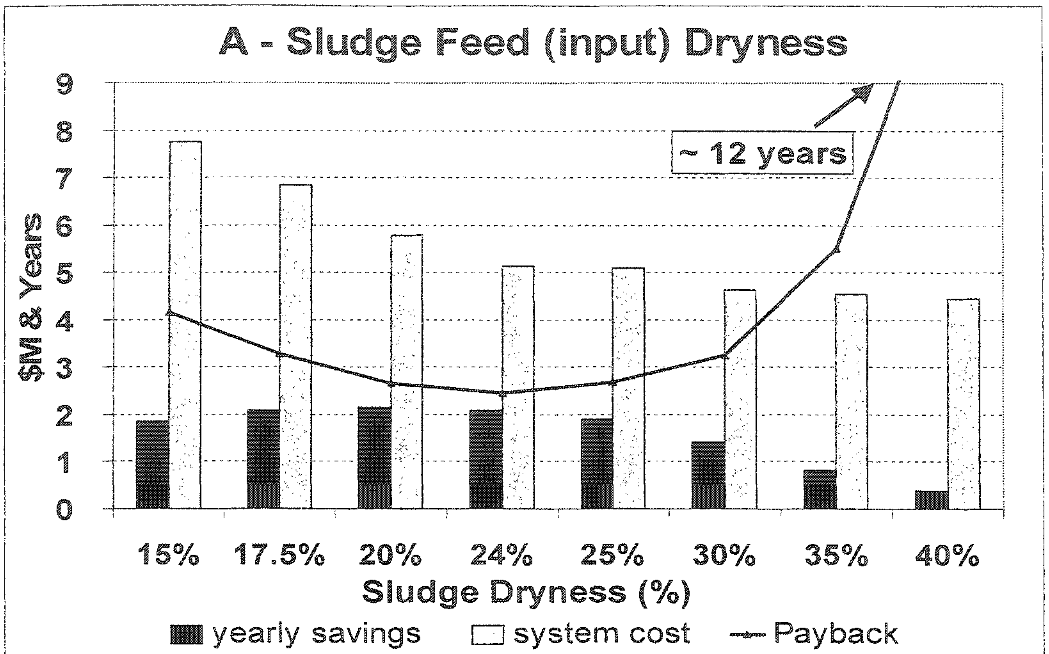

Figure 8.4A: Key Sensitivity Analysis Parameter: Biomass Feed

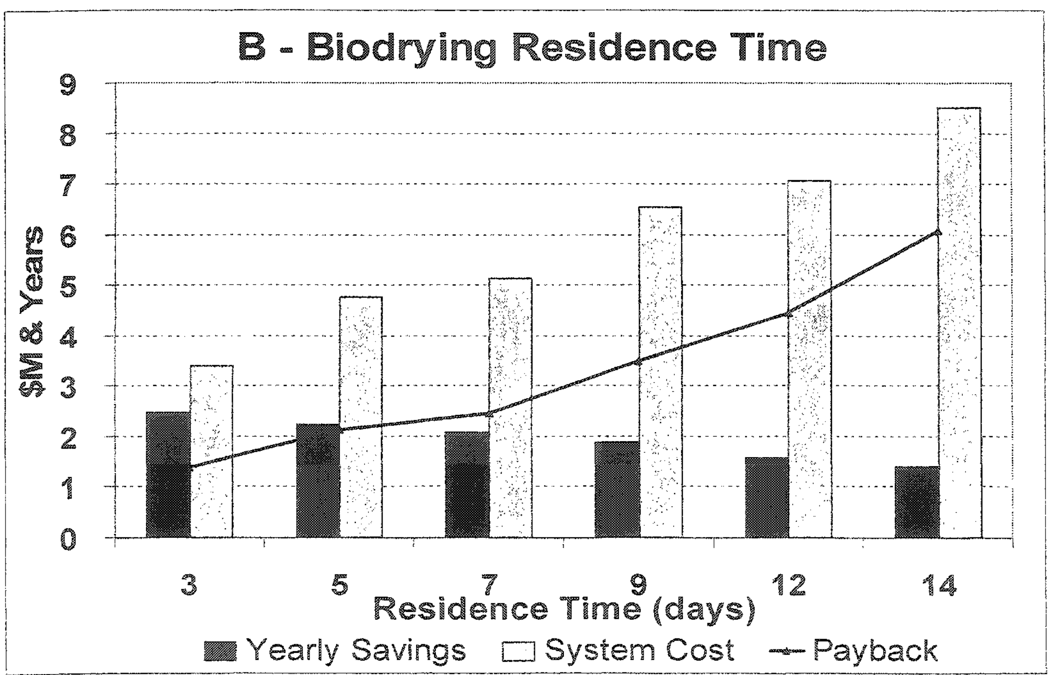

Figure 8.4B: Key Sensitivity Analysis Parameter: Biodrying Residence Time

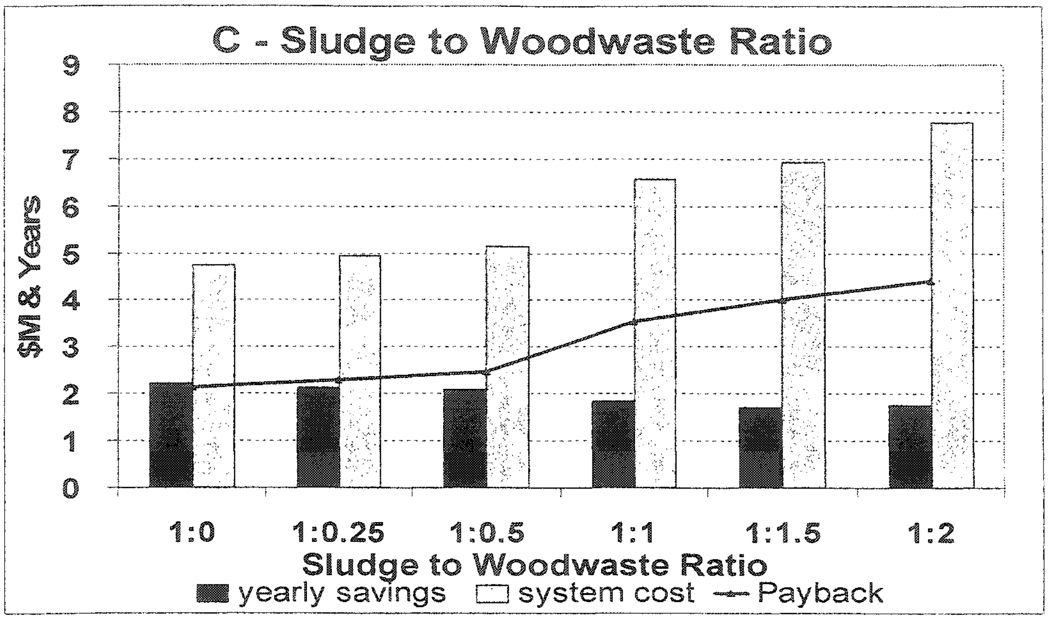

Figure 8.4C: Key Sensitivity Analysis Parameter: Mixing Ratio

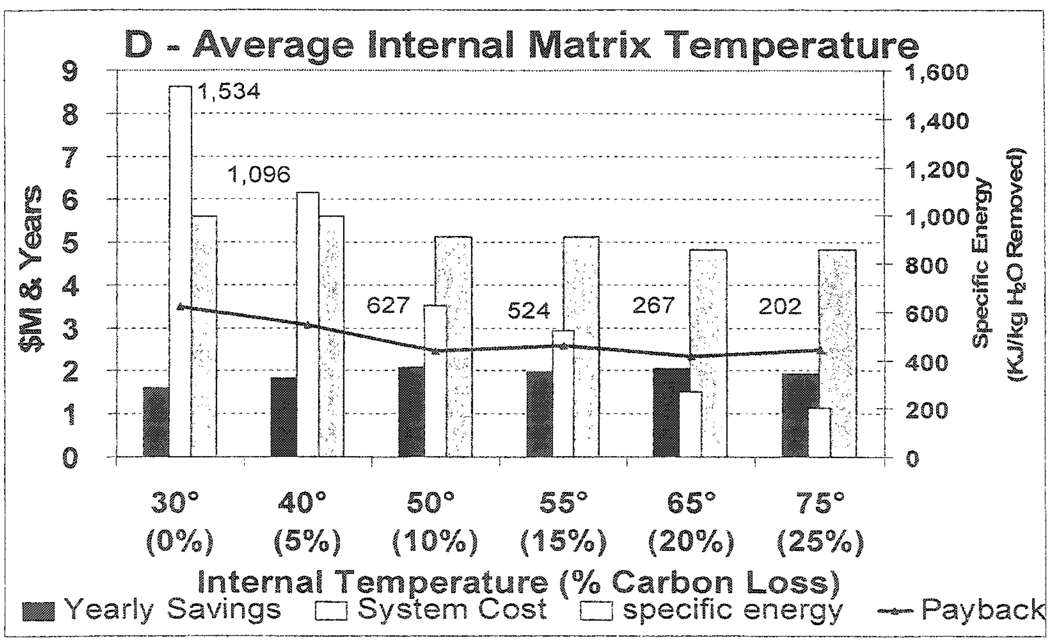

Figure 8.4D: Key Sensitivity Analysis Parameter: Biomass Temperature

The % solids of the feed material (sludge/woodwaste mixture) had the largest impact on yearly savings and project payback. One of the main reasons for this result is that as feed dryness was varied, biodrying outlet dryness was held constant (at 50%), yielding situations where the biodrying system only had to raise the dryness by a minimal amount. In that case, the additional dryness achieved does not represent a major increase in calorific value (see Figure 8.4A at 40% input dryness = 12 year payback). Alternately, a large a dryness differential (e.g. 15% input) would require excessive energy to dry the product. Note that the 7-day residence time was maintained throughout this analysis, as was the 1:0.5 mixture with woodwaste at 50% dryness. The minimum payback period occurs at approximately 24% feed dryness, where there is a balance between the energy required to dry the material, the size and number of reactors, and the increase in fuel value being sent to the biomass boiler.

Biodrying residence time had an impact on the overall system cost as longer drying times resulted in larger and more numerous reactors. Figure 8.4B shows that as the residence time increases, so does the system cost, coupled with slightly decreasing yearly savings due to longer aeration times (and therefore electrical costs).

The ratio to which sludge and woodwaste were mixed had a major effect on the total system cost because the addition of greater amounts of woodwaste to a given amount of sludge resulted in larger overall volumes. Figure 8.4C shows that for mixing ratios in excess of 1:0.5, there is a marked increase in system cost and therefore in the payback period.

The internal temperature is important in the system because, in a large aerated biopile, the extracted air stream will follow the internal matrix temperature (Haug, 1993). The air leaving the reactor is saturated with moisture, and since there is an exponential relationship between the absolute humidity and temperature, warmer air results in faster rates of drying. This in turn reduces the airflow rates required to dry the mixture in a given time period, reducing the size and operational hours of the blowers. Mass balances for the biodrying process (see Section 7) showed that with higher average internal temperatures of the porous matrix, higher rates of carbon loss are observed. So although higher temperatures enhance drying rates, the dried fuel heating value is being reduced due to metabolic activity within the biopile. Figure 8.4D shows the model outputs when the internal temperature and carbon losses are varied. The inputs were selected in order to show the effect of higher temperature/higher carbon loss; however true system carbon losses are dependent on multiple factors (sludge composition, residence time, aeration rates, etc…) and must be evaluated case-by-case. The results indicate that the more biologically active the system is, the more efficient and therefore economical it will be. In addition, Figure 8.4D includes the specific energy consumption (white bars) and shows a decrease with increasing internal temperature. Specific energy consumptions around 500 KJ/kg of water removed are highly competitive when compared to systems such as rotary dryers that consume upwards of 6,000 KJ/kg (Girovich, 1996; Mujumdar and Menon, 1995). The primary saving comes from the elimination of external fuel sources (fossil fuel, etc.), which are replaced by the metabolic energy released by microorganisms consuming the sludge. Electrical energy for blower operation and material handling represent the only energy inputs.

8.5 - Base Case Scenario Variations

Based on the sensitivity analysis results, three scenarios were developed centering on key parameters: a best case, a worst case and a likely system. All scenarios were compared to the base case, and with the following input parameters held constant:

- sludge production = 100 dry tonnes per day at 26% dryness and 700 kg/m^3 density
- woodwaste = 300 dry tonnes per day at 400 kg/m^3 density and 5% ash
- sludge sent to landfill = 16% sent before biodrying, 0% afterwards at $30 per dry tonne
- natural gas consumed per day = 22,000 m^3/day (annual average)
- ambient (biodrying feed) temperature and relative humidity = 20°C and 25% rH

Table 8.5 outlines the input parameters for three scenarios and summarizes the output values.

Worst Case Scenario: long residence time requirement in the reactor and only 45% dryness achieved, low sludge and woodwaste energy content, high woodwaste/sludge mixing ratio of 1:1, low internal drying temperature

Best Case Scenario: short residence time in the reactor and 60% dryness out of biodrying, high sludge and woodwaste energy content, low woodwaste/sludge mixing ratio of 1:0.25, high internal drying temperature, short-distance material handling conveyors

Likely Scenario: similar to base case except that existing material handling facilities at mill (no cost for conveyors and mixing equipment), i.e. likely residence time, likely sludge and woodwaste energy content, likely mixing ratio (1:0.5), 55% dryness out of biodrying, low internal drying temperature

Table 8.5: Biodrying Scenarios Modeled Around Base Case

Parameter	*Worst Case*	*Best Case*	*Likely case*
SLUDGE PARAMETERS			
Energy Content of Sludge	16 GJ/t	24 GJ/t	20 GJ/t
Ash Percentage of Sludge	20 %	5 %	10 %
WOODWASTE PARAMETERS			
Woodwaste Dryness	45%	65%	50%
Energy Content of Woodwaste	16 GJ/t	22 GJ/t	18 GJ/t
Cost of Woodwaste [$/dry t]	$13	$13	$13
ENERGY PARAMETERS			
Cost for Natural Gas	$0.40 /m^3	$0.60 /m^3	$0.42 /m^3
Electricity Cost	$0.045/kWh	$0.039/kWh	$0.039/kWh
BIODRYING PARAMETERS			
Dryness out of Biodrying [%]	45%	60%	55%
Sludge to Woodwaste Ratio for Biodrying	1:2	1:0.25	1:0.5
Biodrying Residence Time	14 days	3 days	7 days
Average Matrix Temperature	40°C	75°C	65°C
Carbon Loss [% of initial dry mass]	5%	10%	10%
GREENHOUSE GAS PARAMETERS			
Cost of CO_2	$10/t CO_{2E}	$50/t CO_{2E}	$30/t CO_{2E}
MATERIAL HANDLING PARAMETERS			
Distance from Dewatering to Biodrying	100 m	50 m	0 m
Distance from Biodrying to Boiler Feed	100 m	50 m	0 m
YEARLY SAVINGS [$ millions]	**$0.9**	**$5.3**	**$2.9**
SYSTEM CAPITAL COST [$ millions]	**$14**	**$3.3**	**$2.9**
DIRECT PAYBACK [years]	**16**	**0.6**	**1.0**
SPECIFIC ENERGY CONSUMPTION [KJ/kg H_2O removed]	**1,046**	**237**	**252**

In the first scenario, the long residence time and high mixing ratio resulted in excessively large volumes of material to be treated over a long period of time, requiring multiple reactors. The need for bark as a bulking agent was so high that supplemental quantities had to be purchased, which reduced operating cost savings. This, combined with a $14 million capital cost, yielded a prohibitive payback of almost 16 years.

In the second scenario, the short residence time (3 days) and low mixing ratio (1:0.25) resulted in smaller volumes of material to be treated, yielding one operational reactor, with one on standby for filling and emptying. Less woodwaste was used for biodrying bulking and the final product was increased in calorific value to such a degree that all fossil fuel and half the bark were eliminated from the boiler, all the while maintaining the same energy production as in the pre-biodrying scenario. This scenario saved the mill over $5 million per year and was relatively low in cost at $3.3 million. This yielded a project that could be repaid in less than one year.

Finally, the third scenario used realistic input values, similar to the base case. The primary difference between the base case and this scenario was that the hardware already onsite was considered in the costing. Many mills that already burn biomass have material handling systems that are easily adapted to biodrying. Thus, the cost of conveyors and mixing equipment were eliminated in this scenario. This setup would create a project that would have a payback of approximately 1 year.

8.6 - Economic Viability of Biodrying Process at Hypothetical Pulp and Paper Mills

In addition to the base case, 9 other hypothetical mills were modeled in order to assess the applicability of biodrying to the industry. Table 8.6 shows each of the 10 (9 + base case) mills, including a brief description of the mill, and the justification for selecting each of them. In general, the justification centers on the type and quantity of sludge produced and its current disposal methods. Clearly other scenarios could be developed, such as those where a mill with no biomass combustion facilities would be required to build one, however hogfuel boilers are assumed to be installed at all ten locations.

Table 8.6: Description of Theoretical Mills

Mill #	***Description***	***Justification***
#1	480 TPD, Groundwood/DIP/ Newsprint mill: Produces 61 TPD of 30% dry sludge with a 22 GJ/t calorific value and 15% ash. 4% of this sludge is sent to landfill with the remainder being burned. No woodwaste is burned with the sludge.	Mechanical mill: Sludge is burned alone at a high calorific value, almost no landfilling
#2	2200 TPD, integrated mill: Produces 55 TPD of 35% dry sludge with a 20 GJ/t calorific value and 5% ash. All of this sludge is sent to be burned. No woodwaste is burned with the sludge.	Chemical mill: Sludge is burned alone at a high calorific value, no landfilling
#3	750 TPD, kraft mill: Produces 20 TPD of 30% dry sludge with a 18 GJ/t calorific value and 5% ash. All of this sludge is sent to be burned. About equal amounts of woodwaste is burned with the sludge.	Chemical mill: Small amount of sludge is burned with bark at a medium calorific value, no landfilling
#4	1500 TPD, Groundwood/Newsprint mill: Produces 61 TPD of 35% dry sludge with a 24 GJ/t calorific value and 10% ash. All of this sludge is sent to landfill and only woodwaste is burned.	Mechanical mill: Shows sludge landfill elimination and then addition to be co-burned with woodwaste. High calorific value for sludge.
#5	1800 TPD, Sulfite/Integrated mill: Produces 100 TPD of 26% dry sludge with a 18 GJ/t calorific value and 10% ash. 16% of this sludge is sent to landfill with the remainder being burned. 300 TPD woodwaste is burned with the sludge. **[Base Case]**	Chemical mill: Wet sludge, some landfill. Low calorific value but large amounts of woodwaste used (3 times as much)
#6	680 TPD, kraft mill: Produces 110 TPD of 25% dry sludge with a 18 GJ/t calorific value and 5% ash. 16% of this sludge is sent to landfill with the remainder being landspread. 153 TPD woodwaste is burned alone	Chemical mill: Wet sludge, low calorific value. All sludge sent offsite. Large amounts of woodwaste used
#7	1520 TPD, TMP/DIP/ Newsprint mill: Produces 78 TPD of 35% dry sludge with a 20 GJ/t calorific value and 15% ash. 70% of this sludge is sent to landfill with the remainder being burned. 51 TPD woodwaste is burned with the sludge.	Mechanical mill: Large production mill. Most of the sludge is landfilled. Once elimination this sludge will also be burned, so will now burn more sludge than bark
#8	1450 TPD, TMP/Newsprint mill: Produces 110 TPD of 40% dry sludge with a 20 GJ/t calorific value and 7.5% ash. All of this sludge is sent to burned. No woodwaste is burned	Mechanical mill: Large production. Large quantities of dry sludge. Shows effect of biodrying where woodwaste must be purchased.
#9	747 TPD, TMP/Newsprint mill: Produces 70 TPD of 25% dry sludge with a 20 GJ/t calorific value and 5% ash. 73% of this sludge is sent to landfill with the remainder being landspread. 51 TPD woodwaste is burned	Mechanical mill: Wet sludge, All sludge sent offsite. Average amount of woodwaste use
#10	352 TPD, TMP/Newsprint mill: Produces 28 TPD of 25% dry sludge with a 20 GJ/t calorific value and 3% ash. 95% of this sludge is sent to landfill with the remainder being landspread. No woodwaste is burned	Mechanical mill: Low production. Small sludge volume, all sludge sent offsite.

Table 8.7 displays the results of the model for all ten mills. The first column briefly summarizes the mill: the first line is the type of mill and its production, the second gives information on the daily sludge output and its characteristics, and the last line gives details about disposal techniques (LF = Landfill, LS= Landspread) and woodwaste usage. The residence time for all scenarios was kept the same at 7 days, as were the temperature and humidity for the feed (20°C and 25%) and outlet (50°C and 100%) streams, the woodwaste energy (16 GJ/t) and ash content (5%), the sludge and woodwaste densities, and the landfilling and landspreading costs. The target dryness and sludge to woodwaste mixing ratio were the same at 50% and 1:0.5 respectively.

Table 8.7: Theoretical Mills Modeled as a Batch Process

# Mill Production (TPD), Mill Type Sludge TPD (dryness, energy, ash) Landfill (LF), Spread (LS), Woodwaste	*Yearly Savings ($ M)*	*System Cost ($ M)*	*Payback Period (years)*	*SEC (KJ/kg water)*
[#1] 480 TPD, Grwd/DIP/News: -61 TPD (30% dry, 22 GJ/t, 15% ash) -4% LF, no woodwaste	**$0.61**	**$3.42**	**5.63**	**690**
[#2] 2200 TPD, Integrated: -55 TPD (35% dry, 20 GJ/t, 5% ash) -No LF, no woodwaste	**$1.59**	**$3.07**	**1.93**	**552**
[#3] 750 TPD, Kraft Pulp: -20 TPD (30% dry, 18 GJ/t, 5% ash), -No LF, 15 TPD woodwaste	**$0.16**	**$2.82**	**17.66**	**831**
[#4] 1500 TPD, Grwd/News: -96 TPD (35% dry, 24 GJ/t, 10% ash) -All LF, 56 TPD woodwaste	**$4.89**	**$4.48**	**0.92**	**651**
[#5 Base Case], 1800 TPD Sulfite Pulp: -100 TPD (26% dry, 18 GJ/t, 10% ash) -16% LF, 300 TPD woodwaste	**$2.07**	**$5.44**	**2.63**	**627**
[#6] 680 TPD, Kraft Pulp: -110 TPD (25% dry, 18 GJ/t, 5% ash) -9% LF, 91% LS, 153 TPD woodwaste	**$2.34**	**$5.55**	**2.37**	**720**
[#7] 1520 TPD, TMP/DIP News: -78 TPD (35% dry, 20 GJ/t, 15% ash) -70% LF, 51 TPD woodwaste	**$3.09**	**$4.61**	**1.49**	**638**
[#8] 1450 TPD, TMP News: -110 TPD (40% dry, 20 GJ/t, 7.5% ash) -No LF, no woodwaste	**$2.53**	**$4.93**	**1.94**	**552**
[#9] 747 TPD, TMP News: -70 TPD (25% dry, 20 GJ/t, 5% ash) -73% LF, 27% LS, 51 TPD woodwaste	**$4.17**	**$5.03**	**1.21**	**737**
[#10] 352 TPD, TMP News: -28 TPD (25% dry, 20 GJ/t, 3% ash) -95% LF, 5% LS, no woodwaste	**$1.87**	**$6.06**	**3.23**	**537**

The following observations can be made from the results presented in Table 8.7. The average yearly savings appear highest in those mills that dispose of most or all of their sludge through either landfilling or landspreading (mills #4, #6, #7, #9). Another characteristic of mills with rapid payback periods is that woodwaste is already present in their operation prior to biodrying (mills #4, #6, #7, #9). It is assumed that all these mills are capable of burning biomass in their existing facilities. Mills that previously sent all their sludge offsite and did not combust woodwaste might not have a biomass furnace. If this equipment is factored in, it is difficult to justify the cost of a biodrying system given the large capital costs associated with installing new combustion technology or extensively retrofitting existing ones.

The mills with the lowest annual savings and longest payback periods are the ones with the lower daily sludge production (mills #3, #10). This indicates that there is a certain economy of scale associated with biodrying. Chemical (kraft, sulfite) mills displayed the poorest results (mills #3, #5, #6), possibly due to low sludge dryness. There is typically less primary sludge being generated from chemical mills, which can account for lower sludge consistencies. Half of the mills (5/10) showed direct payback periods of less than 2 years. Although this is higher than some mills would find acceptable, these payback periods are reasonable for a technology that has yet to proven at full scale. Future pricing related to energy costs, sludge disposal and greenhouse gas emission are all likely to increase, reducing payback periods. In summary, 6 out of the 10 mills have capital costs under $5 million.

8.7 - Continuous Configuration of New Biodrying Process

In order to maintain uniform sludge treatment and to avoid preferential matrix drying, a new continuous biodrying reactor concept has been proposed (see Section 7.3.1). Sludge would be deposited at the top of the reactor, and slowly descend to the reactor bottom, being dried by cross-flow air and eliminating the need for a dedicated standby biodrying reactor for filling and emptying purposes. The continuous reactor could be slightly taller (1 meter of additional matrix height was assumed) than the batch system, because as the material dried, it would be less susceptible to compaction. The potential for increased reactor height permits treating larger sludge quantities using a smaller system footprint. The most significant additional cost for the continuous system would be an automatic material removal system located at the bottom. A traveling screw reclaimer has been proposed for this purpose, due to its proven track record in existing wood and chip handling operations. The addition of automated material removal eliminates the need for a front-end loader and the associated fuel and salary expenses. Air would be supplied at varying flow rates down the reactor, controlled by the air outlet relative humidity (to be maintained at values slightly below 100%). The drying performance was maintained the same as for the batch system, since no continuous system has ever been tested at a mill site or in the laboratory to date. The distinction here is primarily the economics related to capital costs.

Table 8.8 outlines the differences between batch and continuous biodrying process costs related to the results for each of the 10 mill configurations analyzed in the previous section (Table 8.6, 8.7). The same mills were run except using the continuous drying configuration. Residence time, mixing ratios and all other batch operational parameters were kept the same. The analysis was performed on the average values for annual savings, capital costs, and project payback. In addition, the average breakdown of the system components was compared to determine where the greatest savings/costs occurred.

Table 8.8: Comparison Between Batch and Continuous Operation

	Average for 10 Scenarios from Table 8.7		
	BATCH	CONTINUOUS	Difference
Yearly Cost Savings [$M / yr]	$2.33	$2.54	+ 8.3 %
Capital Cost [$M]	$4.54	$3.52	- 22.5 %
Project Payback [yr]	3.90	2.60	- 33.1 %
	Percentage of Total Project Cost		
Biodrying Reactors	20.6%	14.4%	- 30%
Blowers & Piping	13.4%	12.4%	- 8%
Material Handling	42.3%	49.9%	+ 15%
Instrumentation & Control	3.7%	3.3%	- 11%

Continuous operation results in an increase of 8% in annual operating savings, while the total system cost was reduced more than 20%. These two factors combine for approximately 33% average reduction in the project payback periods from 3.9 years to 2.6 years for the 10 mill scenarios (all based on averages). The only system capital cost category that increased was material handling, which is to be expected, as the continuous system employs traveling screw reclaimers to empty the reactors. Reactor pricing is reduced significantly due to the elimination of the standby reactor.

When the 10 mills were modeled as continuous processes, 6 of the 10 mills showed direct payback periods of less than 2 years, a slight increase from the batch configuration. More importantly, despite increased material handling capital costs, all 10 mills had capital costs under $5 million.

8.8 - Conclusions

A novel biodrying process was proposed in which biopile technology previously used for composting and other applications has been adapted for the drying of pulp and paper mill sludge and woodwaste mixtures. If successful, this process could address an important environmental and economic challenge facing many pulp and paper mills. The initial results are very promising, and moreover, there appears to be significant potential for a new continuous reactor configuration.

A technical and economic analysis of the biodrying process was completed to assess its economic viability for various pulp and paper mill scenarios. The operating parameters which had a significant effect on the process included feed dryness, residence time in the reactor, internal temperature maintained in the biomass matrix, and the sludge to woodwaste mixing ratio.

Capitals costs for a batchwise configuration ranged between $3 and $6 million with returns of 1 to 5 years. A proposed continuous operating regime, taking into account automated feed and extraction systems, resulted in more than a 20% savings in capital cost ($2 and $5 million) and a 33% reduction in payback (0.5 – 3 years).

Mills that are more likely to find this process economically attractive include the those that:

- have biomass combustion facilities and related material handling operations already in place
- pay to send their sludge offsite (for either landfilling or landspreading)
- have space available for multiple biodrying reactors, especially located near existing boiler facilities
- would displace fossil fuels for energy production with the process

In the author's opinion, the potential for this technology is promising, particularly in Canada, where there are many opportunities to treat biomass streams. Wastewater sludge is as much a problem in the pulp and paper industry as it is in the municipal sector. Biomass waste stream in the form of woodwaste, forest floor biomass, and agricultural residues are being identified as usable energy sources. Other industries where this process could be beneficial include municipal water and solid waste treatment facilities, composting operations, animal waste (farming) treatment, and contaminated soil treatment.

It is critical that the system be tested at full-scale in order to optimize the process for today's industry. Any mill with biomass management problems that would consider biodrying should first do a thorough audit of their current practices to determine the feasibility of this option. Pilot scale testing (in the 100 m^3 range) is the next logical step before biodrying can advance to the full scale operations described in this section. Since mills produce sludge and woodwaste on a constant basis, it is recommended that the continuous reactor configuration be developed further. Batch tests are fundamental to the understanding of the biodrying process, but continuous operation will better interface with mill systems. The continuous system proposed here is just one of many possible treatment configurations (horizontal, vertical, multi-conduit air injection, supplemental heat addition, etc.), thus more research is needed. The specific challenges facing a future biodrying system center around; drying performance (characterization of heat generation, residence time, etc.), material handling (sticky sludge, compaction that would limit airflow, etc.), and variability of feedstock.

9.0 – CONCLUSIONS

The pulp and paper industry faces challenges with respect to management of their biomass waste streams. Traditional methods of disposal such as landfilling are losing favour given increasing environmental and economic restrictions. Combustion of the waste material on-site appears to be the most promising disposal option for several reasons. Primarily, combustion eliminates the costs associated with sending the waste off-site such as transport, pre-drying and/or pre-treatment prior to disposal. Secondly, energy can be recovered from biological waste, displacing current fuels such as oil and gas; this in turn helps to reduce greenhouse gas emissions related to the Kyoto Protocol. Finally, since biomass combustion has been practiced for many years in this conservative industry, adaptation of the technology is facilitated.

A novel biodrying process was tested in which a biopile technology previously used for composting and similar applications was adapted for the drying of pulp and paper mill sludge and woodwaste mixtures. The initial observations are very promising, and moreover, there is significant opportunity for further process optimization of the batch system in the form of a continuous reactor. This process has the potential to address an important environmental and economic challenge facing many pulp and paper mills.

Good rates of water removal were achieved for different mixtures of paper mill sludge and woodwaste. Sludge drying rates were found to be correlated with the internal temperature reached in the biomass matrix, with warmer, more biologically active mixtures resulting in greater rates of water removal. This temperature increase has an associated increase in carbon loss, and must be balanced against preserving dry mass for energy production through combustion. Pneumatic performance within the matrix was well defined and allowed for meaningful observations. Uniform drying was obtained throughout the reactor, with moderately drier conditions near the aeration conduits. Water removal was linked primarily to convective transport indicated by relatively constant mass loss slopes. As the material dried, it became progressively easier to pass air through the matrix as water was removed from void spaces.

When considering both the mechanisms of moisture removal and material handling, a proposed vertical continuous reactor with variable aeration rates could yield improved drying performance and integration into existing mill systems. While batch tests are fundamental to the understanding of the biodrying process, continuous operation in one form or another should be the eventual design goal.

A technical and economic analysis of the biodrying process was completed to assess its economic viability for various pulp and paper mill scenarios. The operating parameters which had a significant effect on the process included feed dryness, residence time in the reactor, internal temperature maintained in the biomass matrix, and the sludge to woodwaste mixing ratio.

Capitals costs for a batchwise configuration range between $3 and $6 million with returns of 1 to 5 years. A proposed continuous operating regime, taking into account automated feed and extraction systems, results in more than a 20% savings in capital cost ($2 and $5 million) and a 33% reduction in payback (0.5 – 3 years).

Mills that are more likely to find this process economically attractive are those that 1) already have biomass combustion facilities and related material handling operations in place, 2) pay to send their sludge away for disposal, 3) have space available for multiple biodrying reactors, and 4) would displace fossil fuels for energy production with the process.

In the author's opinion, the potential for this technology is promising, particularly in Canada, where there are many opportunities to treat biomass streams. Wastewater sludge is as much a problem in the pulp and paper industry as it is in the municipal sector. Biomass waste streams in the form of woodwaste, forest floor biomass, and agricultural residues are being identified as usable energy sources. More and more, drying of these new energy sources will be the key to extracting maximum value.

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APPENDIX I – EXPERIMENTAL RESULTS PUBLICATION:

Novel Drying Process Using Forced Aeration Through a Porous Biomass Matrix

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Novel Drying Process for Drying Mill Sludge Using Forced Aeration

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NOVEL DRYING PROCESS USING FORCED AERATION THROUGH A POROUS BIOMASS MATRIX

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ABSTRACT

A novel biodrying process was investigated whose goal was to increase the calorific value of pulp and paper wastewater sludge for efficient combustion in woodwaste furnaces. A sludge-woodwaste mixture was dried using forced air, where drying rates were enhanced by the exothermic metabolic activity of aerobic thermophilic microorganisms.

Data was collected throughout the mixture to monitor temperature, humidity, pressure, airflow, and total mass so that moisture and carbon losses could be estimated for three sludge/woodwaste mixtures. A 1:0.5 sludge/woodwaste mass ratio mixture resulted in optimal drying rates, providing favorable pneumatic conditions, and resulting in the most effective removal of moisture compared to 1:1 and 1:0.25 dry-mass ratios. The sludge dry solids content rose from 30.5% to 41.6% in 13 days. Matrix temperature rose as high as 65°C, and it was found that temperature correlated positively with the rate of water removal. Pneumatic conditions improved as the material dried, i.e. permeability increased over time. It was found that the rate of carbon loss was linked to internal heat generation, and the total carbon loss was estimated to be between 5% and 18%.

KEYWORDS

Airflow; Biodrying; Biopile; Carbon; Combustion; Compost; Convection; Energy; Pulp & Paper; Sludge Management; Sludge Drying; Thermophilic; Waste; Woodwaste.

Introduction

The pulp and paper industry is a large consumer of natural resources and produces significant amounts of woodwaste byproducts. Yield optimization and new process technologies are gradually reducing the amount of woodwaste byproduct, but bark and unusable components of the cellulosic raw materials still need to be carefully managed. The energy value in these materials can potentially provide an important opportunity to mills, which is expected to become increasingly valuable as Kyoto Protocol objectives come into regulation.

Activated sludge treatment (AST) is a commonly used and efficient wastewater treatment method employed in the pulp and paper industry. On average across all product types, mills generate about 60 m^3 of wastewater per tonne of paper produced and between 50 and 125 dry kg of wet sludge per tonne of production [1]. It is not uncommon for mills to have in excess of 100 wet tonnes of sludge per day that they must manage. Figure 1 shows a simplified AST system with both the primary and secondary sludge streams. These sludges are typically blended in a chest to form a "mixed sludge" for dewatering. Secondary to primary sludge ratios vary widely but are typically in the 0.4 range, that is, 40% secondary and 60% primary sludge. However, mills are closing water systems and better-segregating and using saleable fibre in the process rather than sending them to sewer. As primary fibre going to treatment is decreasing, wastewater BOD_5 discharges (and associated biological solids production) are increasing as mills incrementally increase their pulp and paper production with time. This combination of events results in an increase in the proportion of secondary sludge. High secondary sludge mixed sludges are more difficult to dewater, especially using screw press technology [2].

INSERT Figure 1

Disposal of mixed sludges is a costly problem for the industry, with combustion and landfilling being the leading disposal methods. Landfilling represents an ongoing cost to the mill without any return (essentially transporting ~75 wt% water to LF site), and is increasingly discouraged from both the environmental and cost perspectives. Combustion, while beneficial to the mill for the production of steam, requires consistent dewatering of the sludge in order to be economically viable, and often requires supplemental fossil fuels to maintain combustion. Table 1 presents waste treatment sludge disposal options and the percentage of mills that use them. Sludge landfilling is employed less-and-less, while combustion and other sludge disposal options are increasing over time in both Canadian and U.S. mills.

INSERT Table 1

Woodwaste has traditionally been combusted in the mill's power boilers, but as landfilling loses favour, more mills are starting to combine mixed sludge from wastewater treatment with bark for combustion [6]. Wastewater sludge can be a viable fuel source once dried above critical levels, possessing heating values (HHV) of 18 to 21 GJ/dry tonne, i.e. equal to or higher than some wood species [6, 7, 8].

The goal of the biodrying process investigated in this study is to dry mixed pulp and paper mill sludges to levels where they can be economically and efficiently combusted in woodwaste boilers, i.e. over approximately 40% dryness, and ideally closer to 50% dryness. The process dries a mixture of sludge and woodwaste using forced aeration, and where sludge-drying rates are enhanced by the exothermic metabolic activity of aerobic, thermophilic microorganisms naturally present with the biomass. In the process concept (Figure 1), mixed dewatered sludge from treatment is combined with bark as a bulking agent, and then fed to the biodrying reactor. Sludge drying is accomplished by the injection and extraction of air in a controlled manner preventing preferential pathways ("channelling").

This biodrying process could potentially provide several economic advantages to the mill, namely (1) fuel savings due to the increased calorific value of dried material, including a reduction in supplemental fuel (typically natural gas and/or oil) to the boiler, (2) reduce or eliminate the requirement for sludge landfilling or landspreading, (3) reduction in greenhouse gas emissions if biomass combustion is considered net-zero for CO_2 emissions, and also (4) a potential decrease in sludge dewatering costs related to lower polymer use (i.e. sludge does not necessarily need to be dried as extensively, leaving water removal to the biodrying process).

1.1 Mechanistic Description of Biodrying Processes

Convection and diffusion represent the main mechanisms by which moisture is transported within the biomass matrix. Convection is related to the temperature, humidity and air flowrate of the carrier gas (air) through the porous matrix, while diffusion from within particles is controlled by temperature and moisture concentration gradients. Figure 2 is a simplified schematic of the mixed sludge and woodwaste matrix. Air (flowing from left to right) carries away moisture through convection from the surfaces of the matrix that it is in contact with. The magnification within Figure 2 schematically details void spaces where water can accumulate, as well as lines of capillary flow between particles and within fibres. After surface moisture has been removed, moisture must migrate from within the individual particles to the surface for evaporation. The drying calculations presented in this paper are limited to psychometric humidity charts and overall water balances.

INSERT Figure 2

Further work on drying of biomass particles has been performed by Zabaniotou [9], Gigler et al. [10], and Saasramoinen and Impola [11]. These authors go into further detail with mathematical models of drying for both constant rate and falling rate zones.

1.2 Thermophilic Aerobic Biological Activity in Biopiles

Aerobic biological activity is essential for the success of the proposed biodrying process. The necessary conditions for good biological activity include appropriate temperature range as well as the presence of adequate air, moisture and nutrients. Investigations related to aerobic sludge composting provide important insight into necessary conditions for the biodrying process.

The ideal temperature range for sludge composting is between 35° and 65°C [12]. This span encompasses a range of different groups of microorganisms that can be categorized according to their temperature tolerances. Figure 3 shows some of the ranges covered by four main groups of microorganisms: the psychrophiles, the mesophiles, the facultative thermophiles, and the thermophiles. For moisture removal in the biodrying process, it is preferable to have as high a temperature as possible, resulting in conditions favouring thermophilic microorganisms.

INSERT Figure 3

Aerobic biodegradation requires uniform and sufficient oxygen transfer throughout the compost matrix to ensure that microorganisms are able to respire at satisfactory levels. For composting processes with drying as the goal, aeration rates must be far in excess (10 to 30 times) of those theoretically required for simple biological oxidation [14]. Air must be properly diffused in the matrix, and be able to reach all pockets of material. Sometimes air will not be able to penetrate into clumps, resulting in local anaerobic conditions. It is useful to differentiate between composting and biodrying in this context. In composting the goal is to degrade the easily accessible organic compounds, typically resulting in a stabilized soil amendment. Composting temperatures are high and oxygen is supplied only in the amounts required to meet the respiration needs of the microorganisms. In biodrying, large amounts of excess air are supplied in order to meet the respiration needs as well as to convey moisture as quickly as possible. Temperatures are lower due to this higher airflow and higher local velocity, which cools the matrix. The carbon consumed throughout the composting process results in a product with less solids overall, possibly reducing bulk calorific value. In biodrying, conditions favouring minimum carbon losses are sought so that energy content can be maintained for dried sludge combustion.

Sufficient concentrations of key nutrients (nitrogen, phosphorus, and other trace nutrients) are required by organisms for proper cell growth. In the proposed biodrying process, the nutrients provided by the biological sludge are available and adequate for good biological activity in the matrix. As the amount of bulking agent (bark woodwaste) increases, the C:N ratio will also increase, and the reduction in rate of biological activity must be balanced against the increased porosity that the bulking agent favours.

The local moisture content of biopiles should be in the range of 40-70% to maintain proper functioning of the microorganisms, as the cell walls must remain permeable to a steady flow of soluble nutrients by osmosis [12, 14, 15]. If the moisture content is too high, oxygen will have difficulty traveling through the matrix, and if it is too low, the microorganisms would exhibit reduced performance.

2. STUDY OBJECTIVES

In order to investigate the feasibility of the proposed biodrying process, three batch experiments were conducted. The main objective of the experiments was to determine the drying characteristics for a (batch) biodrying configuration fed by mixtures of mixed pulp and paper mill sludges and woodwaste, such that:

- Reliable mass balances for water and carbon loss could be completed,
- An appropriate sludge to woodwaste mixing ratio could be determined which results in acceptable pneumatic performance,
- Preliminary results (without process optimization) with respect to overall process performance and drying rates could be obtained, and
- Information could be obtained regarding how the process efficiency might be improved with improved reactor operation and/or design.

3. MATERIALS and METHODS

3.1 Raw Material Characteristics and Preparation

The mixed sludges and woodwaste were supplied by the mill wastewater treatment facilities and related operations of the Tembec Inc. mill located in Témiscaming, Québec. This is an integrated mill producing a range of products from pulp to board to ethanol Mixed sludge production from the mill is approximately 100 dry tonnes per day, with an average solids content of 26%. The mixed sludge is composed of 30% biological sludge and a 70% primary sludge.

Sludge and woodwaste were collected on-site and shipped in large containers. Upon arrival, the sludge and woodwaste were mixed based on mill information concerning the dryness levels of the material shipped, which was later confirmed by moisture content analyses performed on samples sent to an outside laboratory. Table 2 summarizes the sludge mixtures for the three experiments including the difference between the target and actual mixing ratios achieved, the bulk density, and the amount of biological sludge contained in the mixed sludge samples (obtained from data supplied by mill).

INSERT Table 2

There were three distinctly different mixed sludge compositions and three bark types, whose range of characteristics would be important to consider in the design of a full-scale system. The first experiment consisted of mixed sludge with a typical secondary sludge content of 26% and a relatively high sludge dryness of ~30%. This resulted in sticky balls of mixed sludge ranging in size from 2 to 10 cm diameter. The bark for this experiment contained higher than usual large pieces of material that were removed and broken up during mixing to make a more homogeneous mixture. The mixed sludge for the second experiment was wetter (~24%), had a lower secondary sludge content of 17%, and was consequently fluffier. The bark sample consisted of large wood chunks mixed with sawdust. The third experiment of mixed sludge was the wettest (~21%), and had the highest secondary sludge content of 45%. This sludge had a mud-like consistency, making it difficult to mix with the small amounts of bark required for the target 1:0.25 mixing ratio.

3.2 Reactor Set-Up and Experimental Procedure

The $1m^3$ biodrying reactor used for these experiments is shown schematically in Figure 4, and was provided by SOCONAG Inc. Two conduits are located on either side of the reactor and one in the middle. With this patented configuration and appropriate valving, the centre conduit alternately pushes and pulls air, while the two side conduits do the opposite. Temperature (T), pressure (P), relative humidity (rH) and air flowrates were measured in the inlet and outlet air flows. Within the reactor, data were collected at 18 pressure and 9 temperature points. The reactor was separated into two halves, called *A* and *B*, with multi-level probes located at the center point of each half (probes A & B). The mass of the complete reactor was monitored through four 0-1000 kg load cells. During each data acquisition cycle (approximately 10 min.), data from the various sensors were collected and analysed, and the air flowrate was adjusted in order to maintain a constant and equal flow into and out of the reactor.

INSERT Figure 4

The reactor was filled with mixed sludge and woodwaste to a height of 60 cm, and then covered with a plastic membrane in order to seal the system for mass balance purposes. The system was started in the negative flow configuration (shown as "+ – +" in Figure 5 onwards) and flows were adjusted to maintain a slight vacuum (0.005" H_2O) in the headspace above the matrix. This flow configuration was changed approximately every third day to minimize the formation of preferential pathways, and to redistribute the humidity front within the matrix being dried. In order to test the effect of the bulking ratio on the drying performance of the reactor, airflow was kept constant at ~25 SCFM (standard cubic feet per minute) +/- 2 SCFM for all experiments.

4. RESULTS

4.1 Mass Balance Results

The rate of moisture loss was determined in two ways, as follows:

- By measuring changes in the total mass of the reactor with time using the load cells, and
- By calculating a water balance based on the relative humidities of the injected and extracted air streams.

The first method includes mass loss due to both carbon loss (from biological activity) and moisture loss (from drying), while the second method accounts for moisture removal alone.

The mass flow of water in the air streams at any point in time was determined using measurements for the relative humidity, flow and temperature of air with time, as follows:

Mass Flow of Water = Absolute Humidity * Airflow * Wet Air Density (1)

$\mathbf{W}_{in/out}$ [kg H_2O/min] = $\mathbf{H}$ [kg H_2O/kg dry air] * $\mathbf{Q}$ [m^3/min] * $\rho_{wet\ air}$ [kg dry air/m^3] (2)

where the absolute humidity $\mathbf{H}$ is calculated using the relation:

$$H = \frac{18.02}{28.97} \cdot \frac{P_A}{P - P_A} \tag{3}$$

where $\mathbf{P}$ is the atmospheric pressure [Pascals] and $\mathbf{P_A}$ is the partial pressure of water vapour [Pa], calculated using:

$$P_A = \frac{H_R}{100} \cdot P_S \tag{4}$$

where $\mathbf{H_R}$ is the measured relative humidity [%] and $\mathbf{P_S}$ is the vapour pressure of water [Pa] at the measured temperature T [K]. Finally the wet air density is determined using the following:

$$\rho_{wet\ air} = \frac{1}{\frac{22.41}{273} \cdot T \cdot \left(\frac{1}{28.97} + \frac{1}{18.02} \cdot H \right)} \tag{5}$$

Figure 5 shows the mass balance results for moisture into and out of the reactor. The feed air brings in a relatively constant amount of moisture, while the outlet air stream carries with it water removed from the matrix. This generally resulted in a saturated or near-saturated air stream out of the reactor and the rate of moisture removal indicated by the thin black (middle) line in Figure 5.

INSERT Figure 5

Two methods were used to determine carbon balances:

- By measuring the dry solids of representative matrix samples, calculating the total mass before and after each experiment, and assuming all losses of dry mass are carbon,
- By the difference between the total mass loss (measured by load cells) and the estimated moisture loss (see Figure 6).

Table 3 summarizes the amount of water and carbon removed during the second experiment calculated with these two methods, and shows very good consistency in the overall mass balance results.

INSERT Figure 6

INSERT Table 3

4.2 Matrix Drying Characteristics

Figure 6 plots the moisture and carbon mass balances for the second experiment. The two curves begin to diverge as the experiment progresses, indicating an accumulating carbon loss in the form of CO_2 from biological activity.

The slope of the curves in Figure 6 provides the rate of moisture and carbon removal with time, as presented in Figure 7(A). Both curves indicate a relatively constant removal rate initially, which increases as microbial activity increases and the matrix temperature rises (more so for the total mass loss than the water loss). There is an increase in the relative humidity of the outlet air to 100% corresponding to the sustained period of high biomass matrix temperature of about 40°C, trailing off at the end of the experiment when temperature falls off (see Figure 7(B)). Note that the relative humidity of the outlet air drops briefly after changes in air flow direction, likely indicating that dried solids are being re-hydrated by the humid air.

When observing the two rate curves in Figure 7(A), the largest difference (indicated with arrows) is observed following changes in airflow direction, for a period of 10-20 hours as biological activity increases (likely due to the sludge rewetting).

INSERT Figure 7

The average temperature within the matrix can be correlated to the rate of total mass loss from Figure 7(A), as presented in Figure 8, which presents this data for experiment 2. The two curves clearly follow one another. The increased outlet air temperature (as a consequence of the biological activity) allowed for the air to hold greater quantities of moisture, thus increasing the rate of drying.

INSERT Figure 8

Table 4 summarizes the drying performance of all three experiments including the overall mass reductions for both water and carbon on an absolute and daily basis. The second experiment displayed the highest rate of water and carbon removal at 15.4 kg/day and 2.62 kg/day respectively. It also maintained the highest average internal temperature at nearly 43°C, peaking to nearly 65°C. Given that the internal matrix temperatures and carbon losses for experiments 1 and 3 were lower than in experiment 2, it is quite clear that high metabolic activity leads to a more efficient drying system, however this efficiency must be balanced against increased carbon losses that reduce the calorific value of the dried product.

INSERT Table 4

4.3 Matrix Dryness Uniformity

Once each experiment was concluded, 6 samples were removed at each of three reactor heights (10, 30, and 50 cm from the bottom), mixed, and moisture measurements made to determine whether the batchwise experiments had achieved a uniformly dry matrix. Table 5 summarizes the matrix dryness test data from the three experiments. The matrix had dried quite uniformly from top to bottom, however was slightly drier at the bottom in all three experiments.

This could indicate that the matrix near the reactor bottom dries preferentially due to a lower resistance to air flow (the shortest distance between the air ports).

INSERT Table 5

4.4 Matrix Pneumatic Characteristics

The pneumatic performance of the biodrying reactor is critical for good system control and uniform air distribution throughout the matrix.

Darcy's Law [16] describes flow in porous media:

$$\vec{V} = -\frac{K}{\mu}\nabla p \tag{6}$$

where $\vec{V}$ is the fluid velocity (air), μ is the fluid viscosity, $\mathbf{K}$ is the permeability of the porous material, and $\boldsymbol{p}$ is the pressure. Darcy states that for laminar flow in a porous media, the fluid flow is proportional to the pressure drop and inversely proportional to the fluid viscosity and the linear distance traveled.

If the flow between two points is one-dimensional, an acceptable approximation is the following:

$$\nabla p \approx \frac{dp}{dr} \tag{7}$$

allowing for *(6)* to be re-written as:

$$V = -\frac{K}{\mu}\frac{dp}{dr} \tag{8}$$

Darcy's Law was applied to elements for which the differential pressures were known within the biodrying reactor. There were 3 pressure points located between the aeration plenums, on Probes A and B at heights of 10, 30, and 50 cm from the bottom of the reactor (see Figure 4). The mass flow of air through a given element was calculated using the following:

$$m = \rho VA = \rho\left(-\frac{K}{\mu}\frac{dp}{dr}\right)A \tag{9}$$

where $\boldsymbol{m}$ is the mass flowrate in kg/s, $\boldsymbol{\rho}$ is the density of the fluid (air in kg/m^3), and $\mathbf{A}$ is the cross-sectional area traversed by the air. The area is represented as the rectangle that extends from the front of the reactor to the back for a distance of 10 cm above and below each pressure measurement point (see Figure 9).

INSERT Figure 9

If equation *(9)* is applied to each of the i pressure measurement points it yields:

$$m_i = \rho_i \left(-\frac{K}{\mu}\frac{dp}{dr_i} \right) A_i \qquad (10)$$

where the density ρ_i is calculated using the ideal gas law, employing the average pressure between the two pressure points, as follows:

$$\rho_i = \frac{(p_c + p_i)}{2RT_i} \qquad (11)$$

where $\mathbf{R}$ = the gas constant / molar mass of air (8,314 / 29 = 287) and T_i is the temperature in Kelvin.

Laboratory testing [17] has shown that the pressure profile in the reactor varies in a logarithmic fashion across a radial distance $\mathbf{r}$, which yields:

$$p(r) - p_{atm} = \frac{(p_i + p_c)}{\ln(L_i)}\ln(r) + p_c \qquad (12)$$

where L_i is the actual distance in the reactor between two points of element i. Taking the derivative:

$$\frac{dp}{dr} = \frac{(p_i + p_c)}{\ln(L_i)}\frac{1}{r} \qquad (13)$$

and substituting (13) into (10) gives the following:

$$m_i = K_e \sum_{i=1}^{3} \left[\frac{\left(p_i^2 - p_c^2\right)}{2RT_i \ln(L_i)} \frac{A_i}{L_i} \right] \cong m_i = K_e \cdot F_A \qquad (14)$$

where K_e is the effective permeability of the material, equal to the permeability divided by the viscosity of air, and F_A is the lumped summation term. The units of *(14)* are as follows:

$$m_i \left[\frac{kg}{s} \right] = K_e \left[\frac{m^2}{Pa \cdot s} \right] \cdot F_A \left[\frac{kg \cdot Pa}{m^2} \right] \qquad (15)$$

m_i is the mass flow of air through the system, K_e the permeability.

F_A is the force required to move air through a given mass of material. The parameter F_A is plotted versus time in Figure 10. Figure 10(A) represents F_A between the center conduit and pressure measurements on Probe A, while Figure 10(B) is calculated between the side conduits and Probe A (see Figure 4).

INSERT Figure 10

On the forced air side of Probe A [periods "– + –" for 10(A) and periods "+ – +" for 10(B)], the following can be observed:

- The force initially required to move air is larger for the points higher in the matrix where L is greatest,

- F_A decreases significantly with time as the matrix becomes drier between the air entry point and the probe,
- As the matrix becomes uniformly drier and permeability improves, F_A becomes less a function of matrix height (note the arrows in Figure 10), and
- In the last period when the matrix is the driest, the rate of change of F_A is minimum.

On the air extraction side of Probe A [periods "+ − +" for 10(A) and periods "− + −" for 10(B)], the following can be observed:

- F_A increases with time,
- The greatest rate of increase with time is during the second period when the sludge is still wet, and there is the greatest potential for rewetting of dried sludge on the extraction side of Probe A.

From equation *(15)* and the viscosity (α) of air, the matrix permeability **K** can be calculated as follows:

$$K = \frac{m_i \cdot \alpha}{F_A} \qquad (16)$$

Figure 11 shows matrix permeability versus time. The permeability increases significantly during forced air periods, as drying progresses. The permeability decreases during extracted air periods when the sludge is rewetting.

INSERT Figure 11

5. DISCUSSION

In summary, the experimental results indicate the following:

- Mass balances for carbon and moisture around the biodrying reactor have been closed with a high level of certainty,
- Moist air rewets dried sludge when air flow is reversed, resulting in renewed biological activity and increased matrix temperatures for a period of 10-20 hours,
- The rewetting period and increased biological activity is accompanied by an increased rate of carbon loss from the matrix,
- The matrix rewetting is most significant in the earlier periods of the batch experiments when the overall matrix is still quite wet,
- Higher matrix and outlet air temperature permits saturated air to carry more moisture on a mass basis, thus increasing the rate of drying,
- The outlet air is saturated once the matrix temperature rises above a threshold, about 40°C in the of experiment number 2,
- There are indications that air flow preferentially passes via the shortest route between the inlet and outlet air ports, preferentially drying the lower matrix, and

- As the matrix dries, the permeability of the matrix increases dramatically lowering the pressure loss across the matrix and reducing the extent of preferential flow in the lower reactor.
- The second experiment (1:0.5 sludge to woodwaste ratio) displayed improved performance, however this was likely due to particularly favourable sludge characteristics for that experiment (fluffy, low secondary content)

These observations lead to several conclusions that may result in improved process performance of the batch system, as follows:

- There is good opportunity to use higher air flows than in these experiments (while still maintaining higher temperatures and acceptable pneumatic conditions), which could reduce sludge treatment time.
- Temperature spikes were noted after each periodical change in air flow direction (likely due to a rewetting of dry sludge), and there was a clear relationship between high matrix temperatures and rates of drying. This observation indicates that increased overall rates of drying might be achieved if air switching occurs more frequently (say every 10 hours or so) to maintain higher matrix and outlet air temperatures.
- It was found that there was more air passage in the lower portions of the batch reactor configuration than near the top (especially in the early stages of the batch treatment). This observation implies that higher efficiencies and drying rates might be achieved with a new continuous reactor configuration, whose concept is described below.

5.1 New Continuous Reactor Concept

In order to maintain uniform sludge treatment and to avoid preferential matrix drying, a new continuous biodrying reactor concept is proposed as illustrated in Figure 12. Sludge would be deposited on the top of the reactor, and slowly fall to the reactor bottom, being dried by cross-flow air as it falls. The continuous reactor would be taller than the batch system, thereby favouring retrofit installation in crowded mill sites. Sludge charging and discharging technology would be similar to that employed at pulp and paper mills for bark handling.

INSERT Figure 12

Air would be supplied at different flow rates down the reactor, controlled by the air outlet relative humidity (to be maintained at slightly less than 100%). The reactor profiles for matrix permeability, temperature and dryness are expected to be as shown in Figure 12. Higher air flow rates in the upper reactor will convey surface moisture from the sludge matrix at a high rate, maintaining a lower sludge temperature and thereby preserving the higher heating value of the sludge. As the surface water is eliminated, the controlled airflow will reduce, as moisture removal will be limited by diffusion from inside the matrix elements. At this point, provided that there is still adequate moisture and/or nutrients to permit good biological activity, airflow will reduce and the matrix temperature should rise thus accelerating moisture release from inside the matrix elements.

6. CONCLUSIONS

A novel biodrying process was proposed in which biopile technology previously used for composting and other applications was adapted for the drying of pulp and paper mill mixed sludge and woodwaste mixtures. If successful, this process could address an important environmental and economic challenge facing many pulp and paper mills. The initial results are very promising, and moreover, there appears to be significant opportunity for further process optimization of the batch system, and a new continuous reactor has been proposed.

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Table 1: Trends in pulp and paper mill sludge disposal methods

Disposal Method	*1979*	*1988*	*1995*	*1998('94 data)*
	United - States [3]	United - States [3]	United - States [4]	CANADA [5]
Landfilling	87%	70%	51%	53%
Combustion	10%	21%	26%	38%
Landspread	2%	8%	12%	5%
Recycle to Process	<1%	1%	6%	0%
Other Beneficial	<1%	0%	5%	4%

Table 2: Sludge and woodwaste characteristics for each experiment

	Experiment #1	*Experiment #2*	*Experiment #3*
Target Mixing Ratio (dry basis)	1:1	1:0.5	1:0.25
Actual Mixing Ratio (dry basis)	1:1.4	1:0.6	1:0.3
Avg. Initial Sludge Dryness*	30.4%	23.7%	21.3%
Avg. Initial Woodwaste Dryness*	80.0%	62.6%	53.5%
Mixed Sludge Biological Content**	26% (avg)	17% (low)	45% (high)
Initial Mixture Dryness***	47.5%	30.5%	24.5%
Mixed Sludge Bulk Density	~ 550 kg/m^3	~ 600 kg/m^3	~ 800 kg/m^3
Mixed Sludge Description	Dry, chunky	Wet, fluffy	Heavy, wet
Woodwaste Description	Very dry bark	Dry, sawdust-like bark	Moist, sawdust & stringy bark
Overall Matrix Characteristics Notes:	-Strong porous matrix structure -Easy air passage -Little compaction	-Homogeneous mixture -Uniform, small particles led to good pneumatic conditions	-Difficult to mix, resulting in dense matrix -Worst case mixture, almost pure sludge

* Based on 3 composite samples
** From mill data on day of sampling
*** Initial dryness from composites, not calculated

Table 3: Carbon and moisture loss from the matrix calculated with different mass balance assumptions, for the case of the second experiment

ASSUMPTION	*Carbon loss estimate by matrix dryness testing*	*Carbon loss estimate by moisture and total loss measurements*
Carbon (solids) Loss	16%	20%
Water Loss	48%	46%

Table 4: Summary of key results for each experiment

	Experiment #1	*Experiment #2*	*Experiment #3*
Overall Run Duration	11 d	13 d	32 d
Original Solids Content	252 kg	187 kg	190 kg
Estimated Carbon Loss	14 kg (5.5%)	34 kg (18%)	16 kg (8.4%)
Original Moisture Content	280 kg	424 kg	588 kg
Estimated Moisture Loss	150 kg (53.5%)	200 kg (47%)	347 kg (59%)
Average Moisture Loss Rate	13.6 kg/d	15.4 kg/d	10.8 kg/d
Average Matrix Temperature	34.9 °C	42.7 °C	27.5 °C

Table 5: Dryness (%) in samples taken from the reactor at different heights

EXPERIMENT	*#1*	*#2*	*#3*
Initial Composite (3 samples)	47.4%	30.5%	24.5%
50 cm from bottom (6 samples)	60.5%	41.2%	28.8%
30 cm from bottom (6 samples)	65.4%	41.6%	34.3%
10 cm from bottom (6 samples)	65.6%	44.5%	42.0%
Final Composite (3 samples)	65.7%	41.6%	40.5%

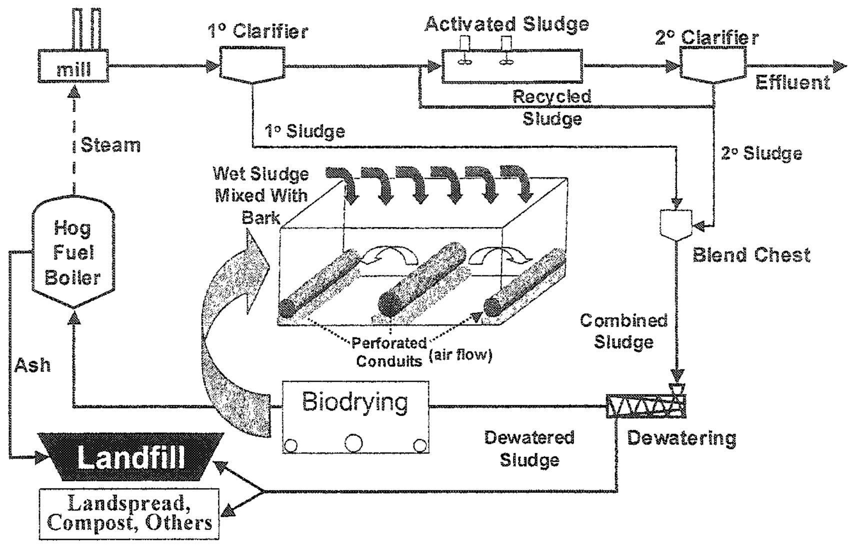

Figure 1: Biodrying process concept integrated into AST process

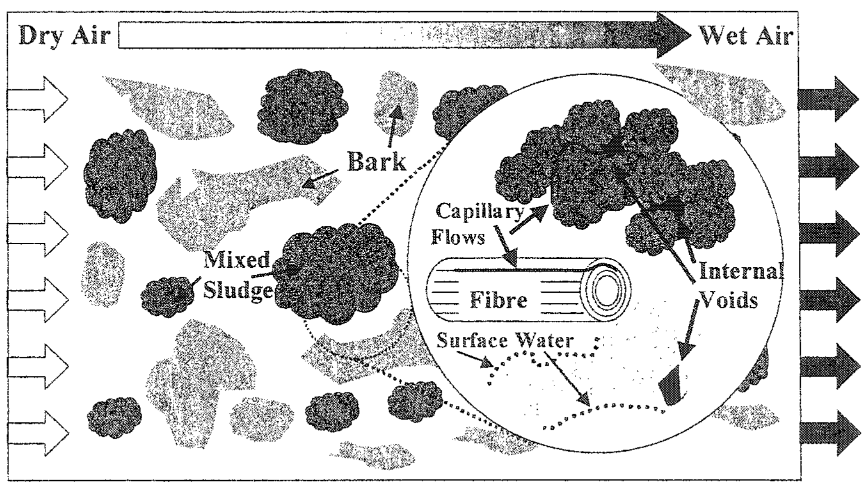

Figure 2: Simplified schematic of the mixed sludge and woodwaste matrix

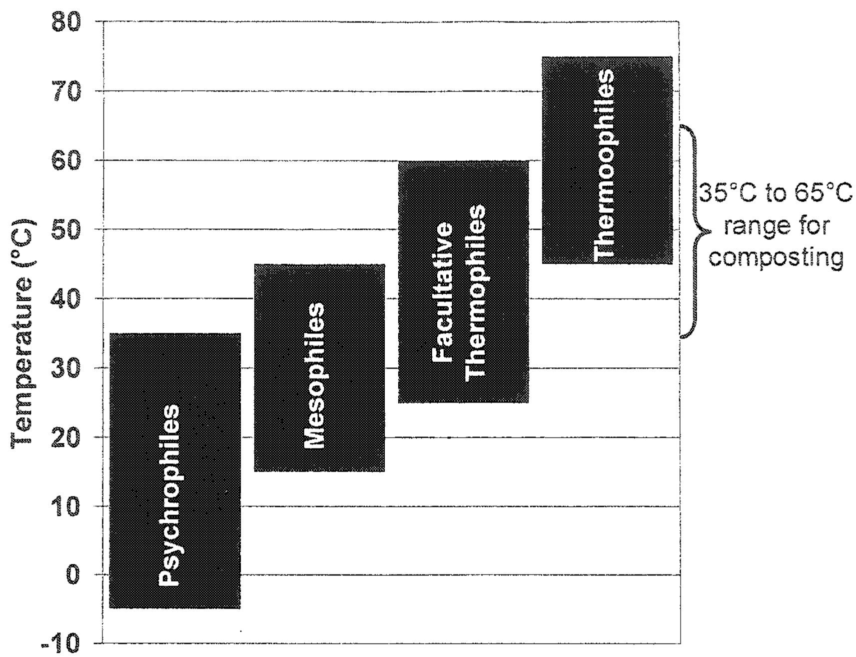

Figure 3: Temperature tolerances for various groups of microorganisms (adapted from Naylor [12] and Pelczar [13])

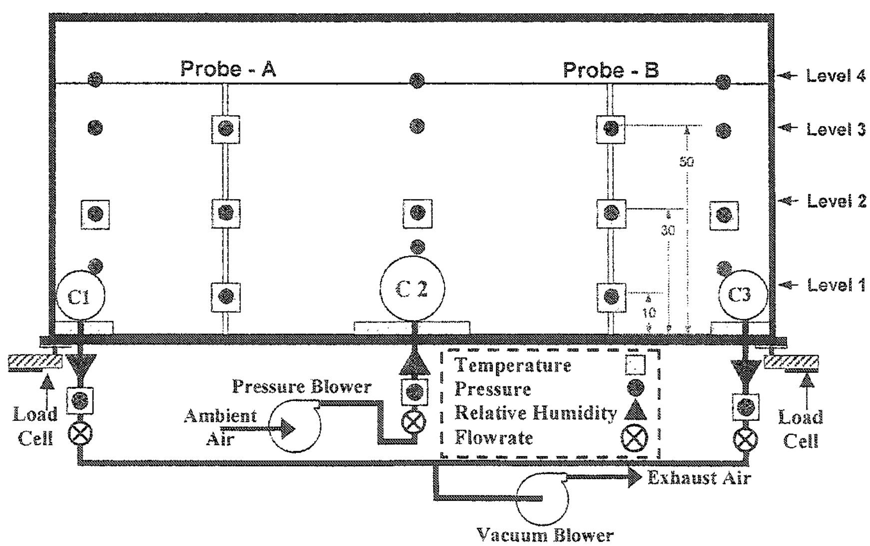

Figure 4: Biodrying reactor schematic

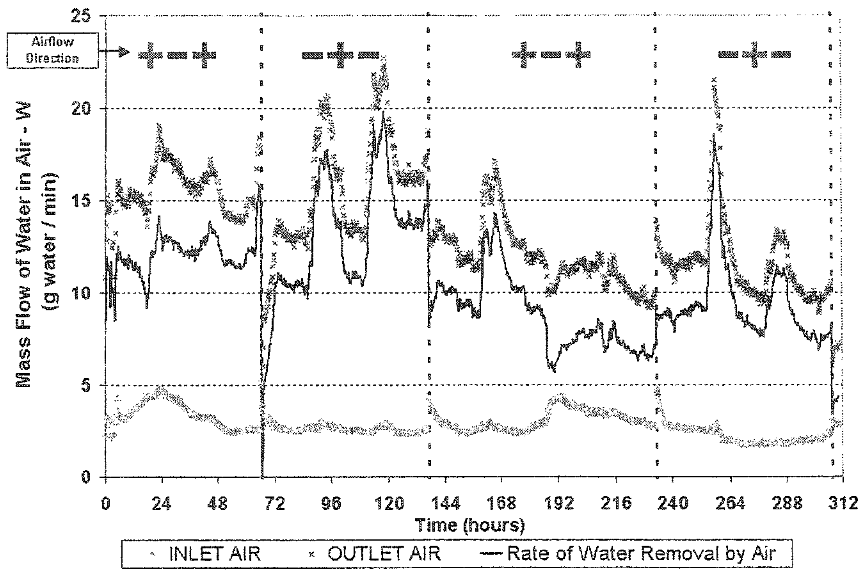

Figure 5: Water mass balance into an out of reactor - Experiment 2

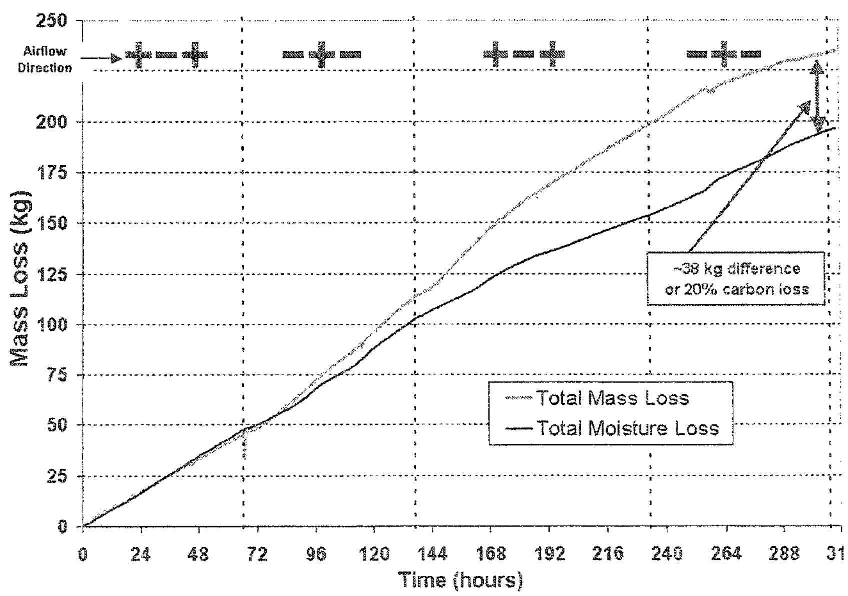

Figure 6: Estimate of carbon loss from mixed sludge - Experiment 2

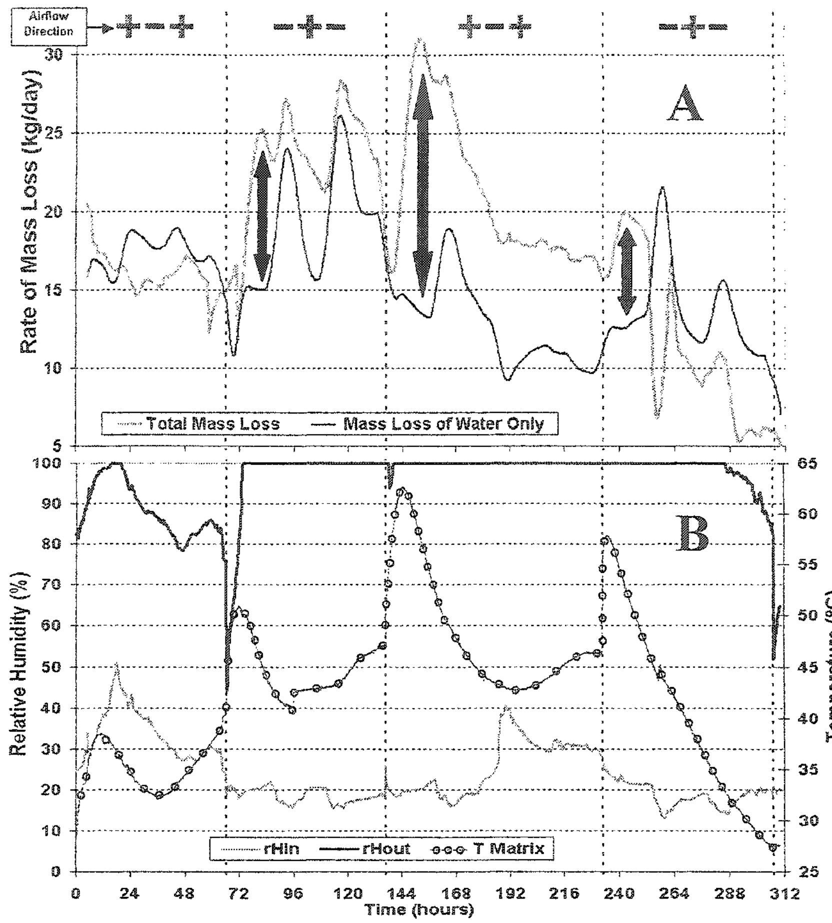

Figure 7: Comparison of (A) total mass loss and water loss with (B) inlet and outlet air relative humidity and matrix temperature - Experiment 2

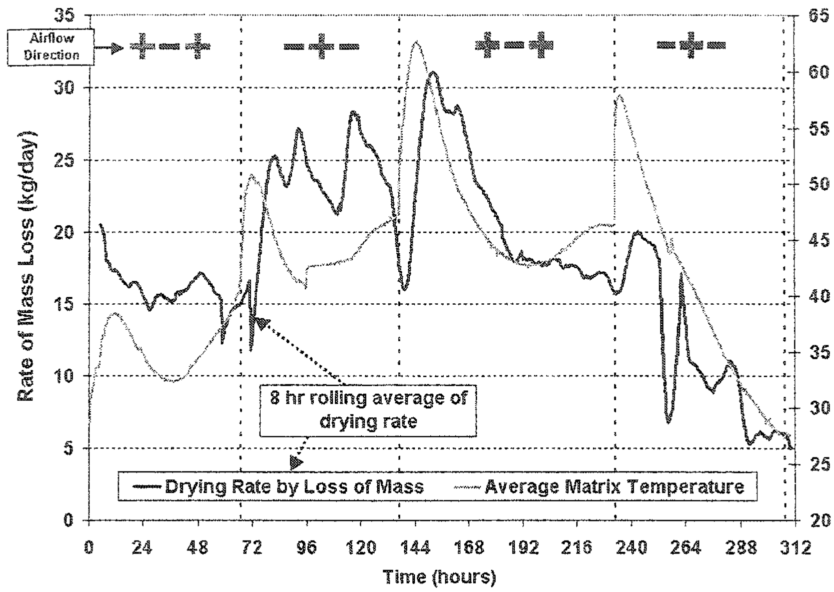

Figure 8: Average internal matrix temperature comparison with rate of drying - Experiment 2

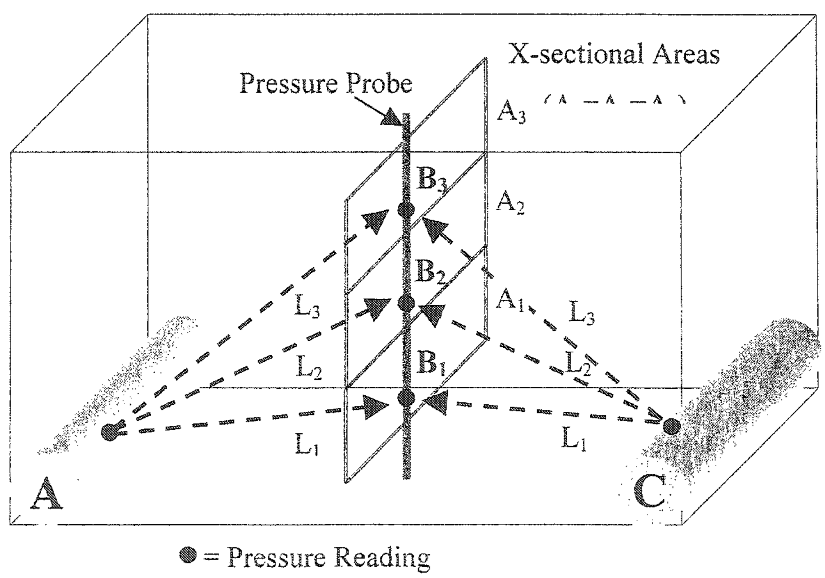

Figure 9: Schematic describing air channels and probe measurements

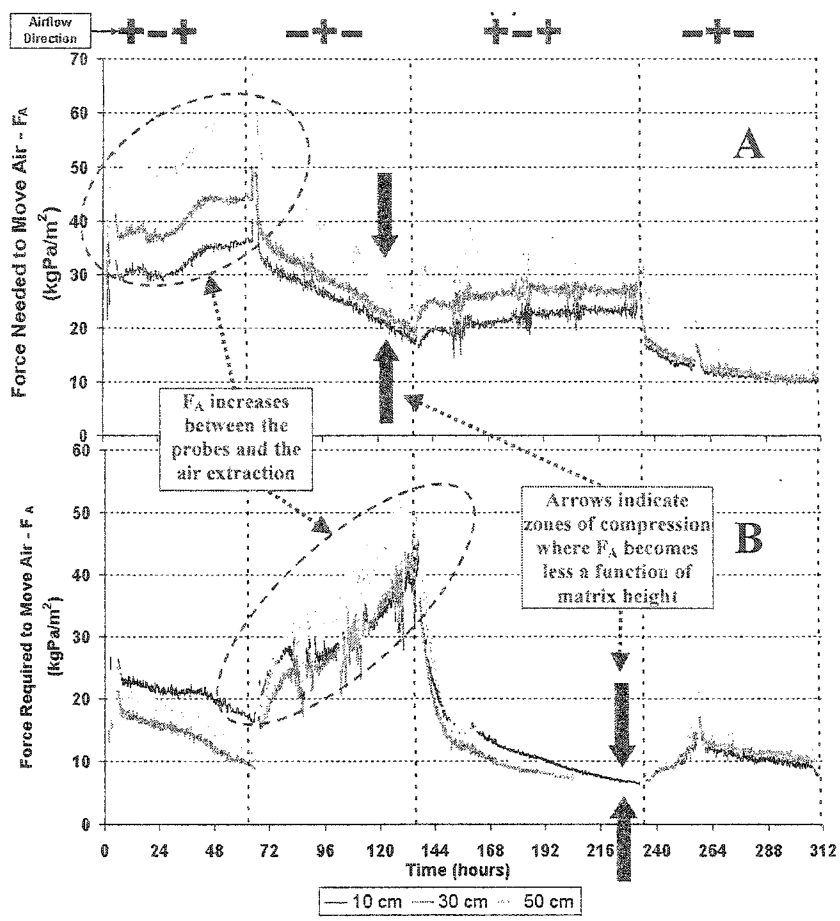

Figure 10: Calculated aeration forces (A) center conduit to probe, (B) side conduit to probe - Experiment 2

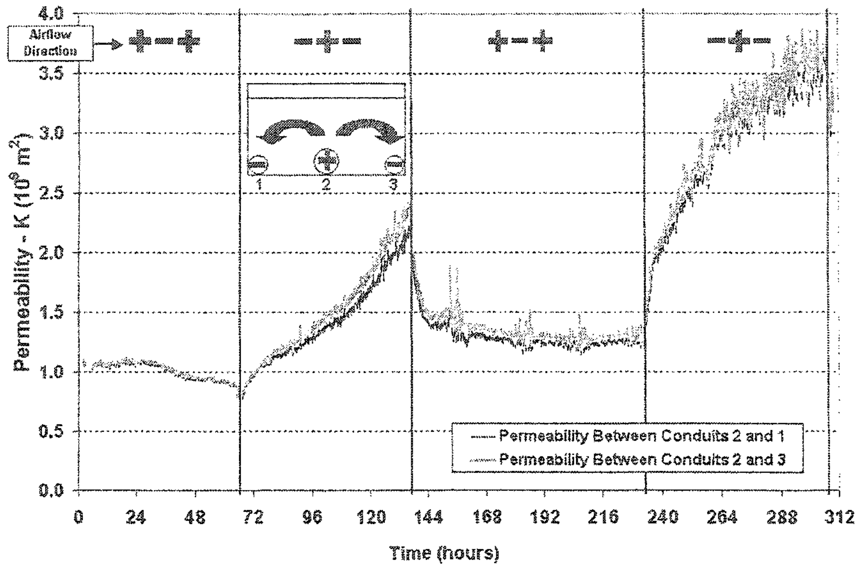

Figure 11: Permeability of the biomass matrix - Experiment 2

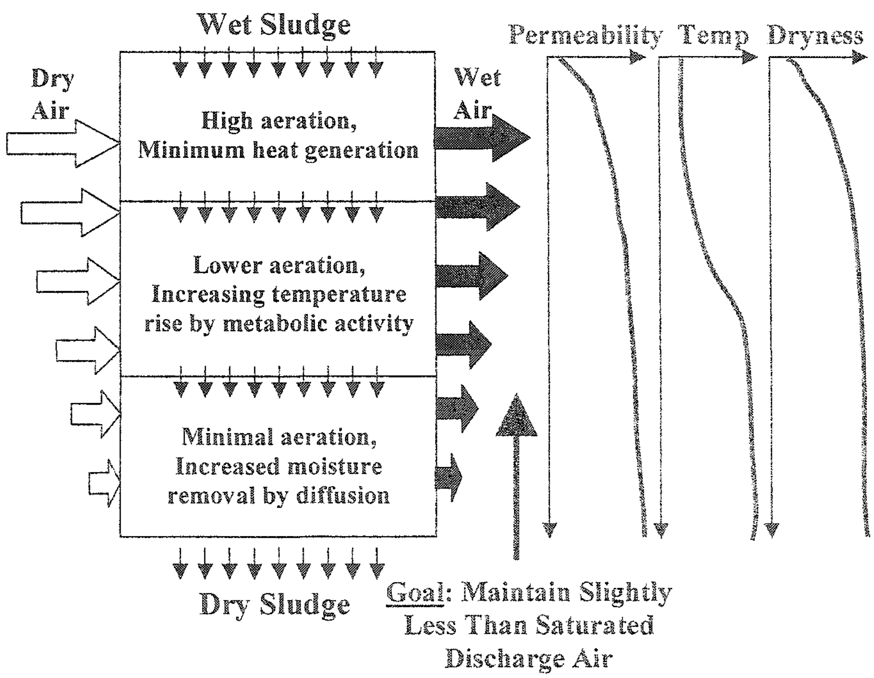

Figure 12: Continuous biodrying reactor concept

APPENDIX II – TECHNO-ECONOMIC PUBLICATION:

Novel Sludge Drying Process for Cost-Effective Onsite Sludge Management

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- Will be submitted for publication in Tappi Journal.

Novel Sludge Drying Process for Cost-Effective Onsite Sludge Management

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ABSTRACT

The large quantities of mixed sludge produced by pulp and paper mills, especially those with high biological sludge content, represent an important opportunity for economic and environmental optimization. A novel biodrying process, which increases the calorific value of sludge by removing moisture so that the mixed sludge can be more economically combusted in the boiler, was investigated. In this "biodrying" process, sludge/woodwaste mixtures are dried using forced air, and drying rates are enhanced by the exothermic metabolic activity of aerobic thermophilic microorganisms.

A techno-economic analysis of the biodrying process is presented in this study. It was found that the critical parameters affecting payback period included the initial moisture content of the sludge and woodwaste, the residence time required for drying, the sludge to woodwaste mixing ratio, and the internal temperature maintained in the biomass matrix. Mills that should most consider this process include those that already possess woodwaste combustion facilities and related material handling operations, that send all or most of their sludge offsite for either landfilling or landspreading, that have space available for multiple biodrying reactors, and/or that have high fossil fuel costs. The simple payback period for implementation of this process at the base case mill was about 2.5 years, and the best case scenarios were found to be 1 year or less.

The study also showed that biodrying system capital costs and payback periods could potentially be significantly lower using a continuous reactor configuration.

KEYWORDS

SLUDGE, PULP & PAPER, DRYING, AERATION, MATERIAL HANDLING, BIOMASS, THERMOPHILIC, BIODRYING, POROUS MEDIA

INTRODUCTION

Disposal of mixed sludge produced from biological wastewater treatment facilities is costly for the pulp and paper industry. A novel biodrying process has been developed that raises the dryness of pulp and paper mill sludge to the point where it can be economically combusted in existing boilers [1]. The process includes an aerated biopile, in which a sludge/woodwaste mixture is dried using forced air, and sludge drying rates are enhanced by the exothermic metabolic activity of aerobic thermophilic microorganisms. This study presents the results of a techno-economic study in which the performance of the biodrying process was simulated, and the capital and operating costs for the installed process were estimated.

Sludge can be a viable fuel source once dried; with higher heating values (HHV) as high as 18 to 21 GJ/dry tonne, i.e. equal to or greater than the HHV of some wood species [2,3,4]. Mills often mix their sludge with bark for combustion [2]. Combustion, while beneficial to the mill, requires extensive dewatering of the sludge to about 40% dryness or higher in order to produce an economically viable fuel source. The activated sludge treatment (AST) process is one of the most commonly used and efficient methods for removing the organic load in pulp and paper mill wastewaters. In the process investigated in this study, mixed dewatered sludge produced by the mill effluent treatment facilities is combined with bark as a bulking agent and then fed to the biodrying process. After drying, the sludge is removed and sent for combustion in a biomass or hogfuel boiler.

DESCRIPTION OF NOVEL BIODRYING SYSTEM

The batchwise biodrying reactor is detailed schematically in Figure 1.

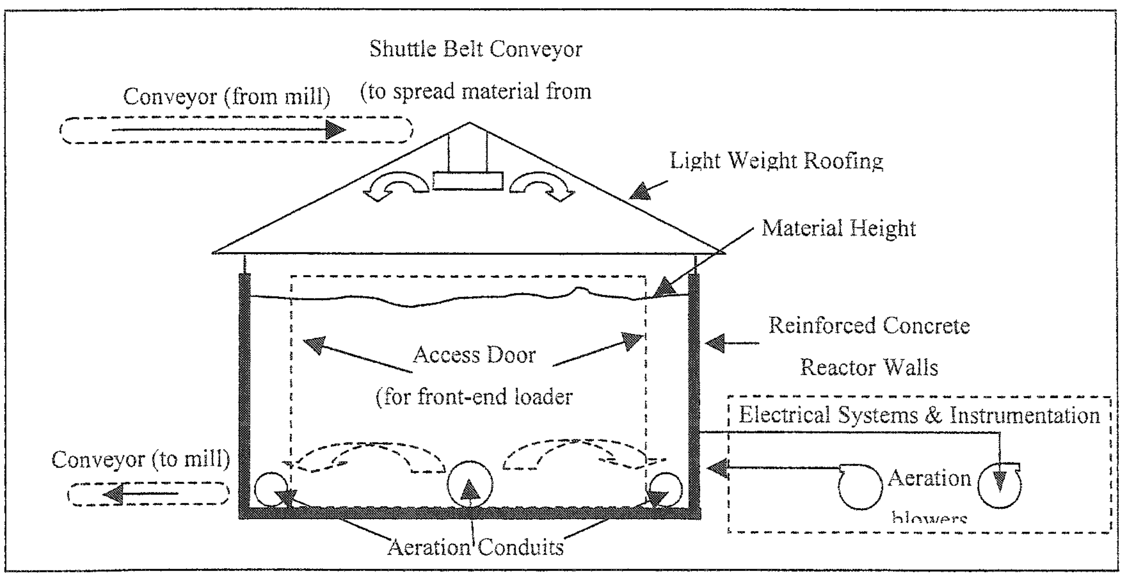

Figure 1: Biodrying Process Schematic

The reactor is sized in order to accommodate the volume of the sludge and woodwaste mixture for an appropriate residence time to ensure drying. The height and width of the unit remain constant (7m x 18m), while the length can be modified, as there is little drying variation in this direction [1]. For the purposes of this design, the mixing of sludge and woodwaste is accomplished using existing mill facilities and the mixture is then transported a short distance (~100 m) to fill the reactors. There the material is applied from the top via a shuttle belt conveyor suspended from the roof of the system (this roof is required to keep precipitation out, but does not have to be sealed). The material is removed after the allotted drying time (~7 days) by opening one side of the reactor and using a front-end loader. Three parallel aeration conduits run along the bottom of the reactor, operating in either the positive (air injection) or negative (air extraction) configurations. These conduits are perforated so that an equal aeration is applied along the length of the aeration plenums. Each reactor is equipped with two blowers (one for air injection and one for air extraction) that pipe air to and from the conduits. The piping system (12" SS) also contains the necessary airflow instrumentation (i.e., flow, temperature, pressure, and relative humidity probes) for aeration control and monitoring.

OBJECTIVE OF THIS STUDY

The objective of this techno-economic study was to interpret the results obtained from bench-scale testing of the novel biodrying process [1], and to evaluate the capital and operating costs associated with a full-scale biodrying system installed at a target pulp and paper mill. The capital and operating costs at various other mill scenarios were subsequently analyzed in order to characterize and identify mills for which this process would be economically attractive.

TECHNO-ECONOMIC ANALYSIS METHODOLOGY

A base case mill was defined from an actual integrated pulp and paper installation, and the capital and operating costs of the biodrying process were calculated based on drying performance data obtained from laboratory experiments [1]. Following this, a sensitivity analysis of parameters in the base case was performed to determine which factors had the greatest effect on the simple payback period. Finally, using this knowledge about critical parameters, various hypothetical but realistic mill scenarios were defined and payback periods were calculated for these mills. The goal here was to identify broad trends in the operation parameters of such a technology, and not so much attribute dollar values to various systems.

CAPITAL COSTS FOR BIODRYING SYSTEM

The full-scale biodrying system is based on the dimensions and shape of the laboratory unit. It was assumed that multiple batch reactors would be required to meet the material flow of a mill, and that the reactors would be installed on level ground within or near the mill complex. The reactors would be placed next to one another, sharing communal systems such as drainage, site access, and electrical substations. While quotes were assembled for the blowers as well as for the instrumentation and material handling systems, the rest of the system was assumed to be fabricated. Unit costs were used for concrete, piping and structures. With the width and height of the reactors fixed, the length was varied in order to adjust the volume of the system. However, the maximum reactor length was set at 35 m, in order to avoid problems inherent to very large systems. These difficulties include the logistics of reactor emptying, and the maintenance of sufficient conduit pressure, which would necessitate extremely large blowers, entailing high capital costs and electrical requirements. Indirect cost factors were applied to the capital cost items and finally a 10% contingency was added.

Table I summarizes some of the primary biodrying system costs, and the asterisks indicate which items represent the most significant expenses.

Table I: Capital Cost Estimate Systems Considered Within Process Battery Limits

Biodrying Reactor	*Reinforced concrete structure, *roofing, site drainage, aeration conduits, access hatch, stairwells, lighting, platforms.
Blowers & Piping	*Pressure and vacuum blowers, piping, valves, air/water separator, electrical systems (MCC, sub-stations)
Material Handling	*Traveling screw reclaimer, *belt conveyors, *shuttle belt conveyor, bark shredder assembly, electrical systems, front end loader
Instrumentation & Control	Sensors (rH, T, Q, P), data acquisition hardware and software
Indirect Capital Costs	Detailed engineering (7%), contractor (4%), construction management (3%), start-up (1%), contingency (10%)

OPERATING COSTS AND SAVINGS FOR THE BIODRYING SYSTEM

The model uses the mill's current sludge generation and disposal practices, assuming a set production rate of sludge with a given moisture content. For the most part, the sludge (@ ~ 20 - 35% dryness) is mixed with purchased bark (@ ~ 50 - 60% dryness) at a ratio of 1:3. The total energy value of the biomass is evaluated based on sludge and woodwaste energy values and the average fossil fuel consumption (used to supplement burning) is also calculated. This gives a pre-biodrying boiler energy value, with the goal being to supply an equal amount of energy to the boiler once biodrying is included. The dried biomass augments the energy being sent to the boiler, allowing for reductions in fossil fuel consumption and thus in operating costs. When sludge characteristics or bark delivery problems impede the mixing of sludge into the boiler feed, the sludge is shunted to landfill or an alternate disposal method. The biodrying system is sized to accommodate all the sludge produced from the wastewater treatment operations, with bark added only as a bulking agent to improve airflow in the reactor matrix. Operating costs are then recalculated. Therefore, the main operating costs of a biodrying system implementation are:

1. **Fossil Fuel**: co-combusted with biomass to increase boiler efficiency
2. **Sludge Disposal**: either landfilling or landspreading operations; boiler ash is typically landfilled
3. **Greenhouse Gas Mitigation**: penalties are accorded for each tonne of CO_2 released as a result of fossil fuel combustion. Savings are realized as less fuel is used. $10/tonne is used here as the potential future value [5]
4. **Electricity**: for the aeration blowers
5. **Material Handling**: for manual sludge handling (front-end loader operator time and fuel)
6. **Labour**: a full-time biodrying operator has been assumed

Without the biodrying process, pulp and paper mills already incur operating costs associated with fossil fuel, sludge disposal, and greenhouse gas mitigation. However, the implementation of the biodrying process will result in significant reductions in these costs. Fossil fuels are subject to ever increasing prices as is sludge disposal off-site. Greenhouse gas (GHG) emissions reductions represent potential future savings as legislation around this issue has not yet been finalized. Items 4 through 6 are costs that are added because of biodrying operation and must be weighed against the benefits of the other three.

TECHNO-ECONOMIC MODELING OF THE BASE CASE MILL

A detailed base case analysis was completed for an 1800 TPD integrated pulp mill located in northwestern Quebec. This mill produces 100 dry tonnes of wastewater sludge per day at 26% dryness on average. Typically, 16% of the sludge is sent to landfill with the remaining 84% being burned in an existing woodwaste furnace. This sludge is currently mixed in a 1:3 ratio with woodwaste (~ 300 dry tonnes per day) and fed into the power boiler. The power boiler is supplemented with 22,000 m^3/day of natural gas, averaged over a yearly basis.

The key assumptions for the base case capital and operating cost calculations include the following:

- The system defined in the base case assumes that a 1:0.5 mixture of sludge and bark is dried from 30% dryness to 50% dryness in 7 days
- The water removed from the sludge-woodwaste mixture increases its calorific value, which results in less fossil fuel being required in the power boiler to meet the same energy output as in the pre-biodrying case
- Sludge landfilling costs are eliminated, with a small increase in ash landfilling due to the residual 16% of the sludge (that was landfilled prior to biodrying) that is now being combusted. The ash content of the sludge is 10%
- Modest CO_2 credits are calculated, taking into account the reduced fossil fuel consumption assuming $10 per tonne of CO_2
- There is an increase in electrical consumption for the aeration blowers and mechanical conveyors
- The operation of a front-end loader for reactor emptying is required

Table II compares the operating costs before and after the implementation of biodrying as well as the capital costs of the system. The top half of the table compares operating costs with and without biodrying, whereas the system capital costs are summarized in the lower half, including the direct payback period for the project. An annual operating cost savings of more than $2 million is realized in the base case scenario. When the annual savings are balanced against the capital costs, the payback period for the base case is approximately two and a half years.

Table II: Operating and Capital Costs Related to Biodrying for Base Case Project

DAILY OPERATING COST ITEMS	*Without Biodrying*	*With Biodrying*	*COMMENTS*
FUEL (fossil & woodwaste) COSTS	**$13,840**	**$5,530**	90% reduction in fossil fuel cost
ELECTRICAL COSTS	-	**$1,665**	2260 total hp for blowers/conveyors
SLUDGE DISPOSAL COSTS	**$1,180**	**$1,680**	No landfill, front-end loader added
GREENHOUSE GAS PENALTIES	**$79**	**$16**	80% reduction from base case
DAILY TOTAL	**$15,100**	**$8,890**	
Yearly Total (365 days)	$5,512,000	$3,244,500	
Yearly savings from base case →	**A**	$2,267,500	
Yearly Biodrying Operating Costs			
Maintenance	**B**	$141,830	3% of total installed cost
Operators:	**C**	$40,000	one @ $40,000 per year
Total yearly costs	**D**	$181,830	**(B + C)**
TOTAL ANNUAL SAVINGS →	**E**	$2,085,770	**(A – D)**
DIRECT COSTS			
Biodrying reactors		$ 1,300,700	(~25% of total capital cost)
Blowers & piping		$ 883,000	(~17% of total capital cost)
Material handling		$ 1,740,000	(~34% of total capital cost)
Instrumentation & control		$ 187,350	(~4% of total capital cost)
TOTAL DIRECT →		$ 4,111,050	
INDIRECT COSTS (%'age of Direct Costs)			
Engineering (7%), Construction (4%), Contractor (3%) Management, & Startup (1%)		$ 616,658	(~12% of total capital cost)
Contingency (10%)		$ 411,105	(~8% of total capital cost)
BIODRYING CAPITAL COST →		**$ 5.14**	Million dollars
PAYBACK (years)		**2.46**	($5.14M divided by **E**)

SENSITIVITY ANALYSIS OF CRITICAL BASE CASE PARAMETERS

The base case represents conservative estimates and realistic performance numbers for the batch biodrying system based on bench-scale results. In order to see how changing various parameters would affect the payback period for this set of assumptions, a sensitivity analysis was performed. Table III further details the input parameters of the base case and shows the ranges used in the sensitivity analysis.

For example, keeping all the parameters at base case values and varying only the biodrying residence time, the total system capital cost varied as follows:

- 3 days = $3.40 million
- 5 days = $4.77 million
- 7 days = $5.14 million (base case)
- 9 days = $6.55 million
- 12 days = $7.07 million
- 14 days = $8.52 million

The variations in capital cost were then compared with simulations where other parameters were varied similarly, and the relative impact was ascertained. In addition to the total capital cost of the system, the performance outcomes considered for the process include: the annual savings incurred by implementing biodrying, the direct payback period, and the specific energy consumption (SEC) of the process. The purpose of this parameter-by-parameter analysis is to identify which ones have the largest effect on the economics of the project. From this exercise, more realistic scenarios that combine multiple parameter variations can be run through the model.

Most of the variables in Table III describe material characteristics (masses, dryness, energy content, etc…) and energy costs and penalties (e.g. greenhouse gas numbers). The parameters that have the greatest effect on the process are those related to biodrying performance, and are based on the experimental work carried out by Frei and Stuart [1].

Table III: Base Case Parameters and Sensitivity Analysis Ranges Supplied to the Techno-Economic Model of the Biodrying Process

Parameter	*Base Case*	*Range*	*Comments*
SLUDGE PARAMETERS			
Sludge Production [t/d]	100	100[a]	dry tonnes / day
Sludge Dryness out of Dewatering [%]	26%	20-40[a]	≅ biodrying feed
Energy Content of Sludge [GJ/t]	18	16 – 24[b]	higher heating value, HHV
Ash Percentage of Sludge [%]	10%	0 – 20%[b]	ash ≅ no energy value
DISPOSAL PARAMETERS			
Percentage of Sludge Sent to Landfill [%]	16%	0 – 100%	% sent before biodrying
Percentage of Sludge Sent to Landspread [%]	0%	0 – 100%	" "
Cost to Landfill [$/dry t]	$30	$15 - $40[c]	incl. transport & tipping
Cost to Landspread [$/dry t]	$25	$10 - $30[c]	incl. transport & tipping
WOODWASTE PARAMETERS			
Woodwaste Usage for Combustion [t/d]	300	300[a]	dry tonnes / day
Woodwaste Dryness [%]	50%	45%-75%[b]	
Energy Content of Woodwaste [GJ/t]	16	14 – 24[b]	HHV per dry tonne
Cost of Woodwaste [$/t]	$13	$13[a]	per dry tonne delivered
Combustion Sludge to Woodwaste Ratio [:]	1:3	1:3	ratio <u>before</u> biodrying
ENERGY PARAMETERS			
Natural Gas Consumed per day [m^3/day]	22,000	22,000[a]	yearly average
Cost for Natural Gas[$/$m^3$]	$0.42	0.40-0.70[a,d]	
Electricity Cost [$/kWhr]	$0.039	0.039-0.06[a,e]	
BIODRYING PARAMETERS			
Product Dryness <u>Out</u> of Biodrying [%]	50%	40% – 65%	set target value
Sludge to Woodwaste Ratio for Biodrying [:]	1:0.5	1:0 – 1:2	for bulking and porosity
Biodrying Residence Time [days]	7	3 – 14	time required to reach outlet dryness target
Average Matrix Temperature [°C]	50°	30° – 75°	≅ biodrying outlet T
Carbon Lost from Start of Biodrying Cycle to the End, [% of inlet dry solids]	10%	0% – 25% [f]	Caused by biological degradation
GREENHOUSE GAS PARAMETERS			
Cost of CO_2 [$/t CO_{2E}]	$10	$5 - $50 [g]	15% of CO_2 production
MATERIAL HANDLING PARAMETERS			
Onsite Distances from mixing to biodrying [m]	100 m	10 – 500[a]	for conveyor costing

a: data supplied by mill	d: National Energy Board of Canada (www.neb-one.gc.ca)
b: synthesized from: McBurney [3]; James and Kane [4]; Kraft and Orender [2]; Nickull et al.[6]; La Fond et al.[7]; Durai-Swamy et al.[8]	e: Hydro-Quebec 2002 Annual Report
c: Scott et al. [9]	f: Carbon consumption based on results from [1]
	g: Browne [5]

From Table III, four key parameters (shaded) were found to affect performance to the greatest degree: biodrying feed dryness (sludge and woodwaste) into the biodrying reactor, biodrying residence time, the sludge/woodwaste ratio, as well as the internal temperature maintained in the reactor throughout drying and the associated carbon loss. Figures 2A-D summarize the sensitivity analysis results for each of these key parameters. For these graphs, the black bars indicate the annual savings, the grey bars indicate the system capital cost, and the black line shows the direct payback in years. Note that values on the y-axis represent both the dollar amounts (in $millions) and the number of years.

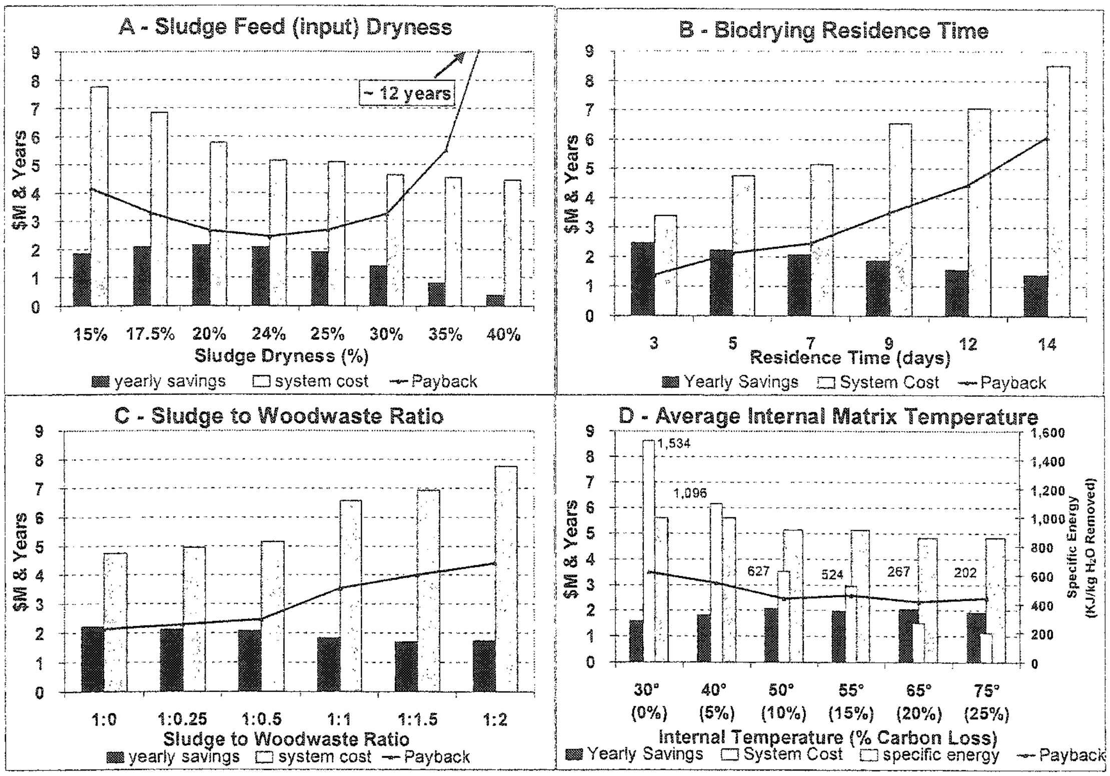

Figure 2: Key Parameters from Sensitivity Analysis

The dryness of the feed material (sludge/woodwaste mixture) had a large impact on yearly savings and project payback. One of the main reasons for this result is that as feed dryness was varied, biodrying outlet dryness was held constant (at 50%), yielding situations where the biodrying system only had to raise the dryness by a minimal amount. In that case, the additional dryness achieved does not represent a major increase in calorific value (see Figure 2A at 40% input dryness = 12 year payback). Alternately, a large a dryness differential (e.g. 15% input) would require excessive energy to dry the product. A minimum payback period occurs at approximately 24% feed dryness, where there is an optimal balance between the energy required to dry the material, the size and number of reactors, and the increase in fuel value being sent to the biomass boiler.

Biodrying residence time had an impact on the overall system cost as longer drying times resulted in larger and more numerous reactors. Figure 2B shows that as the residence time increases, so does the system cost, coupled with slightly decreasing yearly savings due to longer aeration times (and therefore higher electrical costs).

The ratio to which sludge and woodwaste were mixed had a major effect on the total system cost because the addition of greater amounts of woodwaste to a given amount of sludge resulted in larger overall volumes. Figure 2C shows that for mixing ratios in excess of 1:0.5, there is a marked increase in system cost and therefore in the payback period.

The internal temperature is important in the system because, in a large aerated biopile, the extracted air stream will be related to the internal matrix temperature [10]. The air leaving the reactor is saturated with moisture, and since there is an exponential relationship between the absolute humidity and temperature, warmer air results in faster rates of drying. This in turn reduces the airflow rates required to dry the mixture in a given time period, reducing the size and operational hours of the blowers. Mass balances for the biodrying process showed that with higher average internal temperatures of the porous matrix, higher rates of carbon loss were observed [1]. So although higher temperatures enhance drying rates, the dried fuel heating value is being reduced due to metabolic activity within the biopile. Figure 2D shows the model outputs when the internal temperature and carbon losses are varied. The inputs were selected in order to show the effect of higher temperature/higher carbon loss; however true system carbon losses are dependent on multiple factors (sludge composition, residence time, aeration rates, etc...) and must be evaluated case-by-case. The results indicate that the more biologically active the system is, the more efficient and therefore economical it will be. In addition, Figure 2D includes the specific energy consumption (white bars) and shows a decrease with increasing internal temperature. Specific energy consumptions around 500 KJ/kg of water removed are highly competitive when compared to systems such as rotary dryers that consume upwards of 6,000 KJ/kg [11,12].

BIODRYING SCENARIO VARIATIONS

Taking these sensitivity analysis results, three scenarios were developed centering on key parameters: a best case, worst case and a likely system. The following input parameters were held constant:

- Sludge production = 100 dry tonnes per day at 26% dryness and 700 kg/m^3 density
- Woodwaste = 300 dry tonnes per day at 400 kg/m^3 density and 5% ash
- Sludge sent to landfill = 16% sent before biodrying, 0% afterwards at $30 per dry tonne
- Natural gas consumed per day = 22,000 m^3/day (annual average)
- Ambient (biodrying feed) temperature and relative humidity = 20°c and 25% rH

1. **Worst Case Scenario**: long residence time requirement in the reactor and only 45% dryness achieved, low sludge and woodwaste energy content, high woodwaste/sludge mixing ratio of 1:1, low internal drying temperature
2. **Best Case Scenario**: short residence time in the reactor and 60% dryness out of biodrying, high sludge and woodwaste energy content, low woodwaste/sludge mixing ratio of 1:0.25, high internal drying temperature, short-distance material handling conveyors
3. **Likely Scenario**: similar to base case except that existing material handling facilities at mill (no cost for conveyors and mixing equipment), i.e. likely values for residence time, sludge and woodwaste energy content, and mixing ratio (1:0.5), 55% dryness out of biodrying, low internal drying temperature

Table IV outlines the input parameters for three scenarios and summarizes the output values.

Table IV: Biodrying Scenarios Modelled Around Base Case

Parameter	*Worst Case*	*Best Case*	*Likely case*
Energy Content of Sludge	16 GJ/t	24 GJ/t	20 GJ/t
Ash Percentage of Sludge	20 %	5 %	10 %
Woodwaste Dryness	45%	65%	50%
Energy Content of Woodwaste	16 GJ/t	22 GJ/t	18 GJ/t
Cost for Natural Gas	\$0.40 /m^3	\$0.60 /m^3	\$0.42 /m^3
Electricity Cost	\$0.045/kWh	\$0.039/kWh	\$0.039/kWh
Dryness out of Biodrying [%]	45%	60%	55%
Sludge to Woodwaste Ratio for Biodrying	1:2	1:0.25	1:0.5
Biodrying Residence Time	14 days	3 days	7 days
Average Matrix Temperature	40°C	75°C	65°C
Carbon Loss [% of initial dry mass]	5%	10%	10%
Cost of CO_2	\$10/t CO_{2E}	\$50/t CO_{2E}	\$30/t CO_{2E}
Distance from Dewatering to Biodrying	100 m	50 m	0 m
Distance from Biodrying to Boiler Feed	100 m	50 m	0 m
YEARLY SAVINGS [\$ millions]	**\$0.9**	**\$5.3**	**\$2.9**
SYSTEM CAPITAL COST [\$ millions]	**\$14**	**\$3.3**	**\$2.9**
DIRECT PAYBACK [years]	**16**	**0.6**	**1.0**
SPECIFIC ENERGY CONSUMPTION [KJ/kg H_2O removed]	**1,046**	**237**	**252**

In the first scenario, the long residence time and high mixing ratio resulted in excessively large volumes of material to be treated over a long period of time, requiring multiple reactors. The need for bark as a bulking agent was so high that supplemental quantities had to be purchased, which reduced operating cost savings. This, combined with a \$14 million capital cost, yielded a prohibitive payback of almost 16 years. In the second scenario, the short residence time (3 days) and low mixing ratio (1:0.25) resulted in smaller volumes of material to be treated, yielding one operational reactor, with one on standby for filling and emptying. Less woodwaste was used for biodrying bulking and the final product was increased in calorific value to such a degree that all fossil fuel and half the bark were eliminated from the boiler, all the while maintaining the same energy production as in the pre-biodrying scenario. This scenario saved the mill over \$5 million per year and was relatively low in cost at \$3.3 million. This yielded a project that could be repaid in less than one year. Finally, the third scenario used more typical input values, similar to the base case. Many mills that already burn biomass have material handling systems that are easily adapted to biodrying. Thus, the cost of conveyors and mixing equipment were eliminated in this scenario. This setup would create a project that would have a payback of approximately 1 year.

ECONOMIC VIABILITY OF BIODRYING PROCESS AT VARIOUS HYPOTHETICAL PULP AND PAPER MILLS

In addition to the base case, 9 other hypothetical mills were modeled in order to assess the applicability of biodrying to the industry. Table V displays the results of the model for all ten mills. The residence time for all scenarios was kept the same at 7 days, as were the temperature and humidity for the feed (20°C and 25%) and outlet (50°C and 100%) streams, the woodwaste energy (16 GJ/t) and ash content (5%), the sludge and woodwaste densities, and the landfilling and landspreading costs. The target dryness and sludge to woodwaste mixing ratio were the same at 50% and 1:0.5, respectively.

Table V: Theoretical Mills Modeled as a Batch Process

# Mill: Production (TPD), Mill Type: Sludge (dryness, energy, ash) Landfill (LF), Spread (LS), Woodwaste	*Yearly Savings ($ M)*	*System Cost ($ M)*	*Payback Period (years)*	*SEC (KJ/kg water)*
#1: 480 TPD, Grwd/DIP/News: 61 TPD (30% dry, 22 GJ/t, 15% ash) -4% LF, no woodwaste	**$0.61**	**$3.42**	**5.63**	**690**
#2: 2200 TPD, Integrated: 55 TPD (35% dry, 20 GJ/t, 5% ash) -No LF, no woodwaste	**$1.59**	**$3.07**	**1.93**	**552**
#3: 750 TPD, Kraft Pulp: 20 TPD (30% dry, 18 GJ/t, 5% ash), -No LF, 15 TPD woodwaste	**$0.16**	**$2.82**	**17.66**	**831**
#4: 1500 TPD, Grwd/News: 96 TPD (35% dry, 24 GJ/t, 10% ash) -All LF, 56 TPD woodwaste	**$4.89**	**$4.48**	**0.92**	**651**
#5, 1800 TPD Sulfite Pulp:100 TPD (26% dry, 18 GJ/t, 10% ash) -16% LF, 300 TPD woodwaste ****Base Case****	**$2.07**	**$5.44**	**2.63**	**627**
#6: 680 TPD, Kraft Pulp: 110 TPD (25% dry, 18 GJ/t, 5% ash) -9% LF, 91% LS, 153 TPD woodwaste	**$2.34**	**$5.55**	**2.37**	**720**
#7: 1520 TPD, TMP/DIP/News:78 TPD (35% dry, 20 GJ/t, 15% ash) -70% LF, 51 TPD woodwaste	**$3.09**	**$4.61**	**1.49**	**638**
#8: 1450 TPD, TMP News: 110 TPD (40% dry, 20 GJ/t, 7.5% ash) -No LF, no woodwaste	**$2.53**	**$4.93**	**1.94**	**552**
#9: 747 TPD, TMP News: 70 TPD (25% dry, 20 GJ/t, 5% ash) -73% LF, 27% LS, 51 TPD woodwaste	**$4.17**	**$5.03**	**1.21**	**737**
#10: 352 TPD, TMP News: 28 TPD (25% dry, 20 GJ/t, 3% ash) -95% LF, 5% LS, no woodwaste	**$1.87**	**$6.06**	**3.23**	**537**

The following observations can be made from the results presented in Table V. The average yearly savings appear highest in those mills that dispose of most or all of their sludge through either landfilling or landspreading (mills #4, #6, #7, #9). Another characteristic of mills with rapid payback periods is that woodwaste is already present in their operation prior to biodrying (mills #4, #6, #7, #9). It is assumed that all these mills are capable of burning biomass in their existing facilities. Mills that previously sent all their sludge offsite and did not combust woodwaste might not have a biomass furnace. If this equipment is factored in, it is difficult to justify the cost of a biodrying system given the large capital costs associated with installing new combustion technology or extensively retrofitting existing ones.
The mills with the lowest annual savings and longest payback periods are the ones with the lower daily sludge production (mills #3, #10), indicating that there is a certain economy of scale associated with biodrying. Chemical (kraft, sulfite) mills displayed the poorest results (mills #3, #5, #6), possibly due to low sludge dryness. There is typically less primary sludge being generated from chemical mills, which

can account for lower sludge consistencies. Half of the mills (5/10) showed direct payback periods of less than 2 years. Future pricing related to energy costs, sludge disposal and greenhouse gas emission are all likely to increase, reducing payback periods. In summary, 6 out of the 10 mills have capital costs under $5 million.

CONTINUOUS CONFIGURATION OF NEW BIODRYING PROCESS

In order to maintain uniform sludge treatment and to avoid preferential matrix drying, a new continuous biodrying reactor concept has been proposed [1]. Sludge would be deposited at the top of the reactor, and slowly descend to the reactor bottom, being dried by cross-flow air and eliminating the need for a dedicated standby biodrying reactor for filling and emptying purposes. The most significant additional cost for the continuous system would be an automatic material removal system located at the bottom. A traveling screw reclaimer has been proposed for this purpose, due to its proven track record in existing wood and chip handling operations. The addition of automated material removal eliminates the need for a front-end loader and the associated fuel and salary expenses. Air would be supplied at varying flow rates down the reactor, controlled by the air outlet relative humidity (to be maintained at values slightly below 100%).

Table VI outlines the differences between batch and continuous biodrying process costs related to the results for each of the 10 mill configurations analyzed in the previous section (see Table V). The same mills were run except using the continuous drying configuration. The analysis was performed on the average values for annual savings, capital costs, and project payback. In addition, the average breakdown of the system components was compared to determine where the greatest savings/costs occurred.

Table VI: Comparison Between Batch and Continuous Operation

	Average for 10 Scenarios from Table VII		
	BATCH	CONTINUOUS	Difference
Yearly Cost Savings [$M / yr]	$2.33	$2.54	+ 8.3 %
Capital Cost [$M]	$4.54	$3.52	- 22.5 %
Project Payback [yr]	3.90	2.60	- 33.1 %
	Percentage of Total Project Cost		
Biodrying Reactors	20.6%	14.4%	- 30%
Blowers & Piping	13.4%	12.4%	- 8%
Material Handling	42.3%	49.9%	+ 15%
Instrumentation & Control	3.7%	3.3%	- 11%

The only system capital cost category that increased was material handling, which is to be expected, as the continuous system employs traveling screw reclaimers to empty the reactors. Reactor pricing is reduced significantly due to the elimination of the standby reactor. When the 10 mills were modeled as continuous processes, 6 of the 10 mills showed direct payback periods of less than 2 years, a slight increase from the batch configuration. More importantly, despite increased material handling capital costs, all 10 mills had capital costs under $5 million.

CONCLUSIONS

A novel biodrying process was proposed in which biopile technology previously used for composting and other applications has been adapted for the drying of pulp and paper mill sludge and woodwaste mixtures. If successful, this process could address an important environmental and economic challenge facing many pulp and paper mills. The initial results are very promising, and moreover, there appears to be significant potential for a new continuous reactor configuration. Wastewater sludge is as much a problem in the pulp and paper industry as it is in the municipal sector. Biomass waste streams in the form of woodwaste, forest floor biomass, and agricultural residues are being identified as usable energy sources.

A technical and economic analysis of the biodrying process was completed to assess its economic viability for various pulp and paper mill scenarios. The operating parameters which had a significant effect on the process included feed dryness, residence time in the reactor, internal temperature maintained in the biomass matrix, and the sludge to woodwaste mixing ratio. Capitals costs for a batchwise configuration ranged between \$3 and \$6 million with returns of 1 to 5 years. A proposed continuous operating regime, taking into account automated feed and extraction systems, resulted in more than a 20% savings in capital cost (\$2 and \$5 million) and a 33% reduction in payback (0.5 – 3 years).

Mills that are more likely to find this process economically attractive include the those that:

- have biomass combustion facilities and related material handling operations already in place
- pay to send their sludge offsite (for either landfilling or landspreading)
- have space available for multiple biodrying reactors, especially located near existing boiler facilities
- would displace fossil fuels for energy production with the process.

It is critical that the system be tested at full-scale in order to optimize the process for today's industry. Since mills produce sludge and woodwaste on a constant basis, it is recommended that the continuous reactor configuration be developed further. The specific challenges facing a future biodrying system involve: drying performance (characterization of heat generation, residence time, etc…), material handling (sticky sludge, compaction that would limit airflow, etc…), and variability of feedstock.

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