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Magnetically Assisted Gasification of Solid Waste

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ABSTRACT

A variety of techniques, including supercritical water oxidation, fluidized bed combustion, and microwave incineration have been applied to the destruction of solid wastes produced in regenerative life support systems supporting long duration manned missions. Among potential problems which still deserve attention are the need for operation in a variety of gravitational environments, and the requirement for improved methods of presenting concentrated solids to the reactor. Significant improvements in these areas are made possible through employment of the magnetically assisted gasification process. In this paper, magnetic methods are described for manipulating the degree of consolidation or fluidization of granular ferromagnetic media, for application in a gravity independent three step solid waste destruction process. Solids are first concentrated from an aqueous slurry using a depth filter in which the particles of filtration media are stratified according to size and consolidated for maximum filtration efficiency using magnetic forces. The organic material within the entrapped solids is destroyed by a combination of pyrolysis, isomerization, and oxidation reactions in a fluidized bed reactor. Finally, inorganic solids are removed by reverse-flow fluidization and collected on a downstream filter.

INTRODUCTION

Initial investigations have demonstrated the feasibility of the Magnetically Assisted Solid Waste Filtration and Gasification technology. As illustrated in Figure 1, the process consists of three sequential steps: 1) filtration of suspended solid particulate matter from an aqueous slurry, using a bed of granular ferromagnetic filtration media; 2) destruction of the entrapped particulate matter using a combination of pyrolysis, isomerization, and oxidation reactions; and 3) removal and collection of the by-product inorganic solids (ash) from the ferromagnetic media by fluidization in the reverse flow direction, followed by downstream filtration. In each of these three steps, the degree of bed consolidation or fluidization can be controlled using magnetic forces. Significantly, magnetic forces can be used to either augment or oppose gravity. In the absence of gravity, magnetic forces can be used to provide a gravity-like restoring force. Thus, by using a sophisticated design to produce the required magnetic fields and magnetic field gradients, ferromagnetic materials can be fluidized in either upflow or downflow directions under a variety of gravitational environments, including microgravity.

This three step process offers several distinct advantages for application in a closed loop life support system, as compared to other current technologies such as supercritical water oxidation[1-7], fluidized bed combustion[8], and microwave incineration9,10. In the first two technologies, high solids loadings in the aqueous phase are required to achieve efficient reactor operation. However, the rheological properties of aqueous solid waste suspensions make it very difficult to pump slurries with high solids content. For this reason, feeding the reactors becomes a very problematic operation. Thus, secondary hardware is required to produce high solids pumpable slurries, such as by acid hydrolysis. Significantly, a high degree of solids loading is not required for the Magnetically Assisted Filtration and Gasification process because solids are concentrated by the filtration step. Thus, an aqueous loop, cycling between the solid waste source and the magnetically consolidated filtration media can function effectively, even at low solids loadings.

Another advantage of the proposed system is that, through the combination of pyrolysis, reforming (isomerization), and combustion reactions, the formation of problematic gaseous by-products requiring secondary treatment, such as SO2, SO3, and NOx, can be minimized. Also, the microgravity and hypogravity compatibility of the proposed Magnetically Assisted Filtration and Gasification process is substantially better than that of other current solid waste treatment technologies. The ability to continuously vary magnetic field strength will provide sufficient overall flexibility that a single system can be operated in a variety of gravitational environments, such as zero *g* during a Mars transit, and 0.6 *g* on the Martian surface.

To facilitate development of magnetic methods for control of the degree of fluidization or consolidation of granular media, several completely new forms of ferromagnetic materials have been successfully prepared. Neutrally buoyant ferrite loaded calcium alginate beads, containing hollow glass microspheres, were produced to facilitate experiments under microgravity-like conditions. New materials of this kind may serve as excellent supports for immobilization of enzymes and whole cells in magnetically stabilized bioreactor applications. High surface area cobalt impregnated barium titanate beads, and spheres composed of pure metallic cobalt were also produced. These materials may be well suited in a variety of industrial applications as ferromagnetic catalysts and catalyst supports for employment in magnetically stabilized fluidization based processes.

Because both magnetic fields and magnetic field gradients are necessary to provide the magnetic forces required to control the degree of consolidation or fluidization of the ferromagnetic media, the primary challenge during the initial investigation was to develop means for producing suitable magnetic field gradients. This was accomplished very successfully using electromagnets consisting of a linear series of Helmholtz coils to produce nearly constant field gradients in the axial direction. This represents completely original work which, in addition to the needs of the current solid waste destruction project, makes practical a wide variety of other magnetically stabilized fluidization applications. Additionally, the utility of the use of permanent ring magnets, in several alternative configurations, was confirmed for controlling both consolidation and fluidization of magnetic media in gas-solid and liquid-solid contacting regimes.

Several reactors were designed and assembled for investigation and demonstration of the individual component operations of the solid waste gasification process. These reactors were equipped with magnetic field generators and were tested using a variety of ferromagnetic particles. The removal of inedible plant biomass from an influent aqueous slurry using magnetically consolidated filtration beds was confirmed in separate experiments using systems incorporating both electromagnets and permanent magnets. Magnetic manipulation methods were also developed to produce a bed of filtration media which is stratified by particle size, with the largest particles near the inlet of the filter and the smallest particles near the outlet. This resulted in improvements in filtration efficiency as compared to the performance of a bed of randomly distributed media.

The complete destruction of the organic components of wheat straw, which had been previously separated from an aqueous suspension by the filtration step in a magnetically confined bed of iron-nickel alloy beads, was achieved by combustion using air to feed oxygen to the bed under magnetic control. The production of CO_2, H_2O, and gaseous organics was confirmed using on-line instrumentation. Following combustion, a reverse direction magnetically controlled displacement of the bed was conducted in air and the ash removed from the system was collected on a down-stream filter. Following this step, visual examination of the bed indicated a complete removal of all unreacted material. Visual and microscopic examination of the material collected on the filter indicated the presence of ash.

PREPARATION OF FERROMAGNETIC MEDIA

The fundamental relations defining magnetic flux density (**B**) and magnetic field intensity (**H**) are given by,

$$\mathbf{H} = \frac{\mathbf{B}}{\mu} = \frac{p}{4\pi r^2}\ \hat{\mathbf{i}} \tag{1}$$

In magnetic media, flux density,

$$\mathbf{B} = \mu_o\left(\mathbf{H} + \mathbf{M}\right) = \mu_o\left(\mathbf{H} + \chi_m \mathbf{H}\right) = \mu \mathbf{H} \tag{2}$$

is a function of both the field intensity and the magnetization,

$$\mathbf{M} = \chi_m \mathbf{H} \tag{3}$$

In ferromagnetic media, magnetic susceptibility is not constant, but varies as a function of both the applied field strength the magnetization history of the material (hysteresis), and temperature.

Table I. Curie Temperatures of Ferromagnetic Metals (°C)

Nickel	358
Iron	770
Cobalt	1121

Three magnetic properties are required for the media to be used for the Magnetically Assisted Filtration and Gasification process: 1) high magnetic susceptibility - the material must be easily magnetized, 2) high Curie temperature - the material must not lose magnetization at reactor temperature, and 3) low coercivity - the material must be easily demagnetized. Curie temperatures for several high permeability/low coercivity ferromagnetic metals are shown in Tables I. Cobalt, with a Curie temperature of 1121°C, is clearly superior from the standpoint of high temperature operation. For this reason two approaches have been investigated for the production of cobalt based magnetic media: the preparation of cobalt impregnated barium titanate, and the production of metallic cobalt spheres. Scanning electron micrographs of these two materials are shown in Figures 2 and 3, respectively. Ferrite impregnated calcium alginate beads were prepared for room temperature experimentation. Neutrally buoyant calcium alginate beads were also prepared using hollow glass microspheres to approximate microgravity conditions.

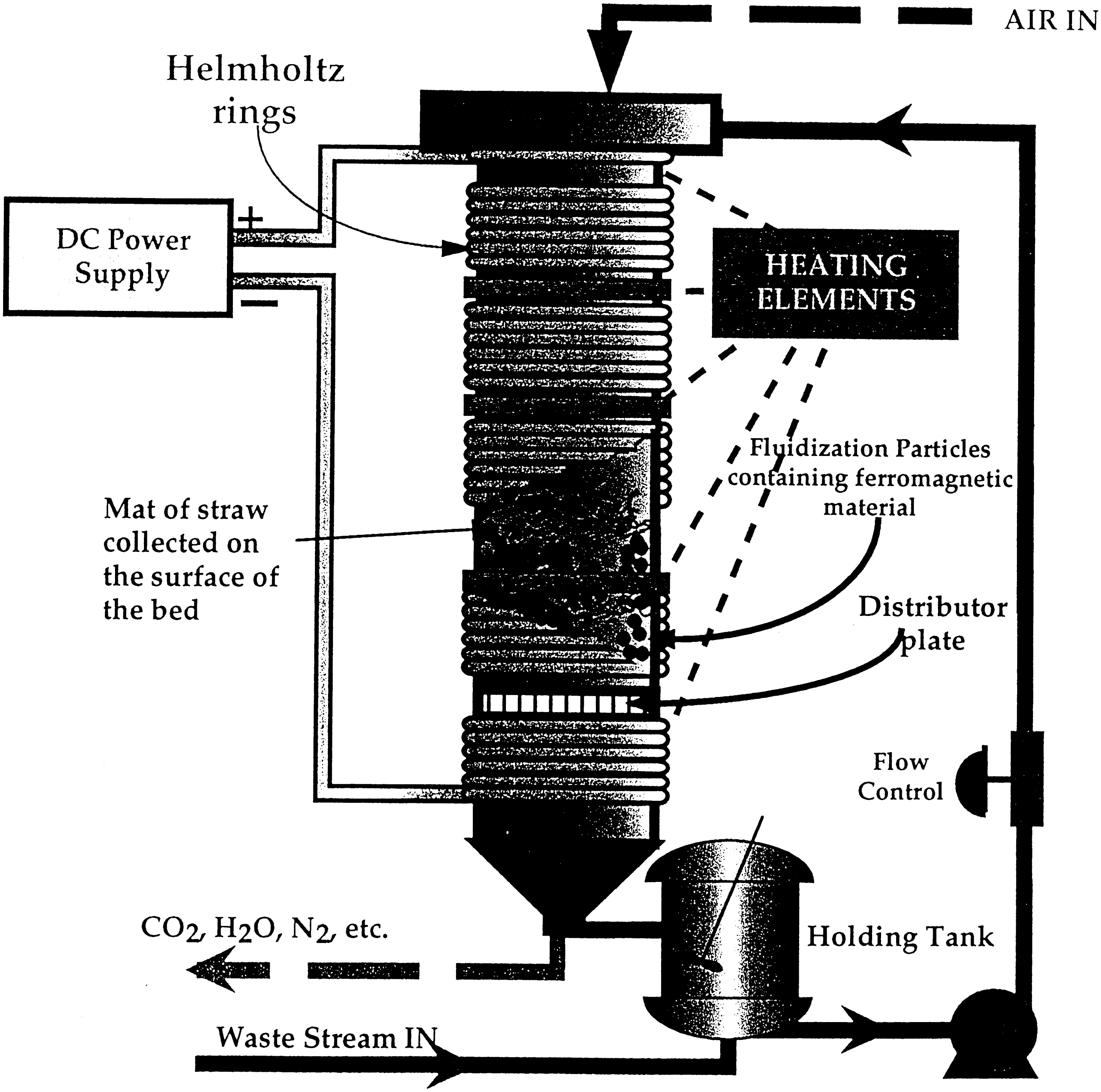

Figure 1. Three Step Magnetically Assisted Solid Waste Destruction Process

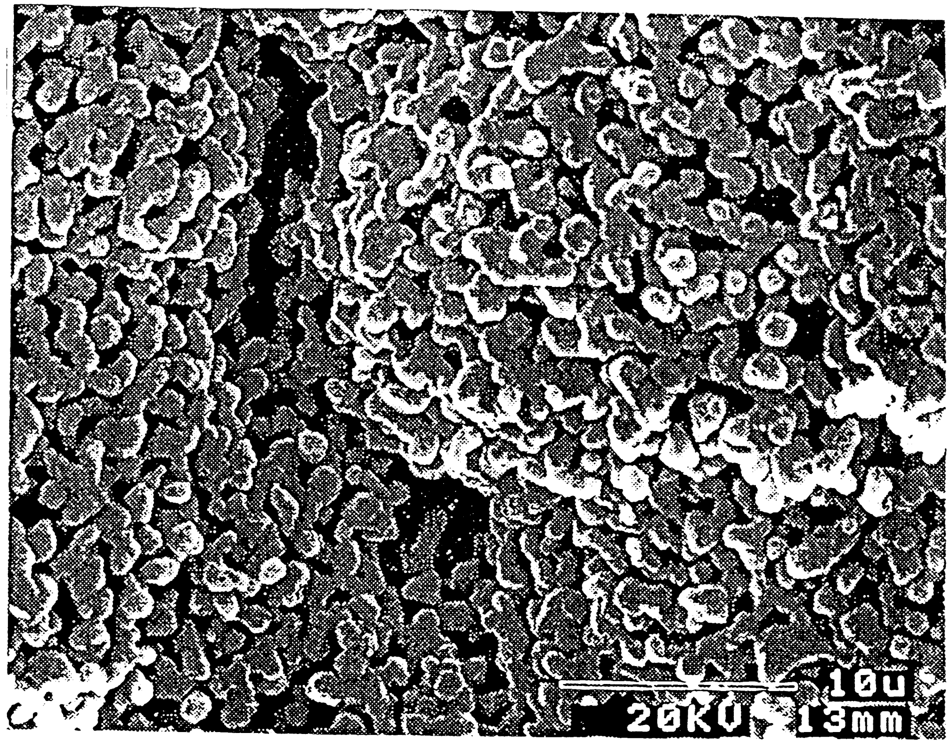

Figure 2. Surface SEM Photomicrograph of Cobalt Impregnated Barium Titanate Bead

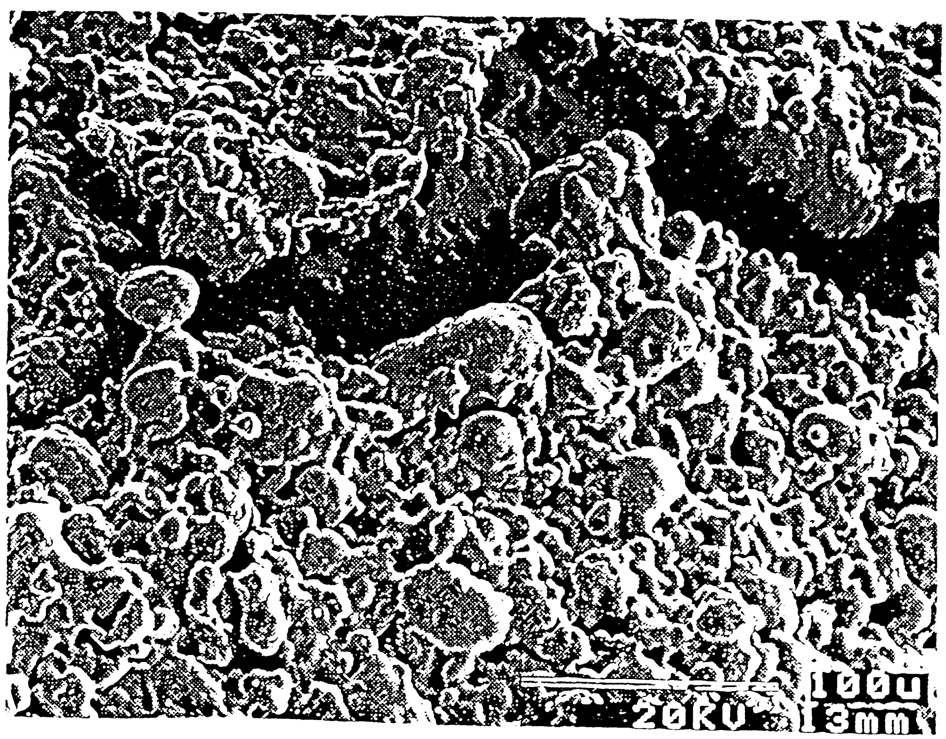

Figure 3. Surface SEM Photomicrograph of Porous Cobalt Bead

MAGNET DESIGNS

Two types of magnetic force are encountered in the Magnetically Assisted Solid Waste Filtration and Gasification process. In the presence of an external magnetic field, individual magnetic particles act as small magnets, and exert forces upon one another, as described by,

$$\mathbf{F} = \frac{\mu}{4\pi} \frac{p_1 \; p_2}{r^2} \hat{\mathbf{i}} \tag{4}$$

This is a secondary phenomenon which occurs in both homogeneous and non-homogeneous fields. The primary magnetic force,

$$\mathbf{F_v} = \nabla \mu_o \left(\chi_m \;\; \mathbf{H} \bullet \mathbf{H} \right) = \nabla \left(\mathbf{M} \bullet \mathbf{B} \right) \tag{5}$$

requires both a strong magnetic field (to magnetize the susceptible media) and a field gradient to produce the force acting upon the magnetized particles.

A Helmholtz coil is a device consisting of two identical solenoids in-line and with current flowing in the same direction, separated by 1 solenoid radius. A very uniform **Bz** is produced across the gap between solenoids. However, both useful field strengths and field gradients have been produced using a series of Helmholtz rings. The individual and combined axial field strengths (**Hz**) as a function of position for an electromagnet composed of eight Helmholtz coils are shown in Figure 4. This unique electromagnet design, which produces a very nearly constant field gradient along the length of the device, was used in the design of the Constant Gradient Magnetic Field (CGMF) test apparatus which is discussed in the following section.

The use of electromagnets is advantageous for experimental purposes because of the ease with which the magnetic field intensity can be controlled by regulation of the current. However, to minimize energy consumption, it is anticipated that the solid waste treatment device which ultimately results from the development effort will use permanent magnets. For this initial investigation, permanent ring magnets composed of barium hexaferrite have also been evaluated for the confinement and manipulation of granular magnetic media.

REACTOR DESIGN AND ASSEMBLY

Several magnetically controlled reactors were constructed to investigate the unit operations and functions required for the Magnetically Assisted Solid Waste Filtration and Gasification System.

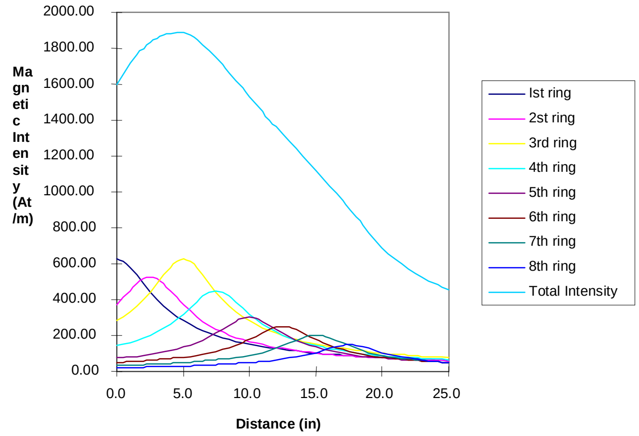

Figure 4. Axial Field Intensity for System of Eight Helmholtz Coils.

CLOSED COLUMN MAGNETICALLY STABILIZED FLUIDIZED BED (MSFB) WITH NON-HOMOGENOUS MAGNETIC FIELD (CC-MSFB) – A small MSFB was constructed to study the motion of neutrally buoyant fluidization particles in a column containing a weak Bingham plastic fluid, used to compensate for small density differences between ferromagnetic particles and the fluid. In this mode of operation (CC-MSFB), the fluid and particles are confined within the fluidization column. Figure 5 shows the strength of the field along the central axis of the combined solenoid. The suspension of neutrally buoyant particles in this system is illustrated in Figure 6. Since the axial length of the solenoid is small (short solenoid), the generated field is predominantly non-homogenous. Thus, when ferromagnetic particles are exposed to this field, they experience a magnetic force, proportional to the field gradient, according to (5), which is oriented toward the center of the solenoid. This causes motion of the particles toward the end of the column which is centered within the solenoid. The magnetic force acting on a single particle is proportional to the field gradient as well as to the mass of ferromagnetic material per unit volume of the particle. This force, which sets particles in motion, is opposed by the drag force between moving particles and the fluid. The drag force is proportional to the relative velocity of fluid and particle (laminar flow) and to the particle surface area to mass ratio. Since larger particles have smaller surface area per unit mass, they reach higher settling velocities than smaller particles. Thus, conditions are created for the segregation of particles while they are settling under the influence of the magnetic field.

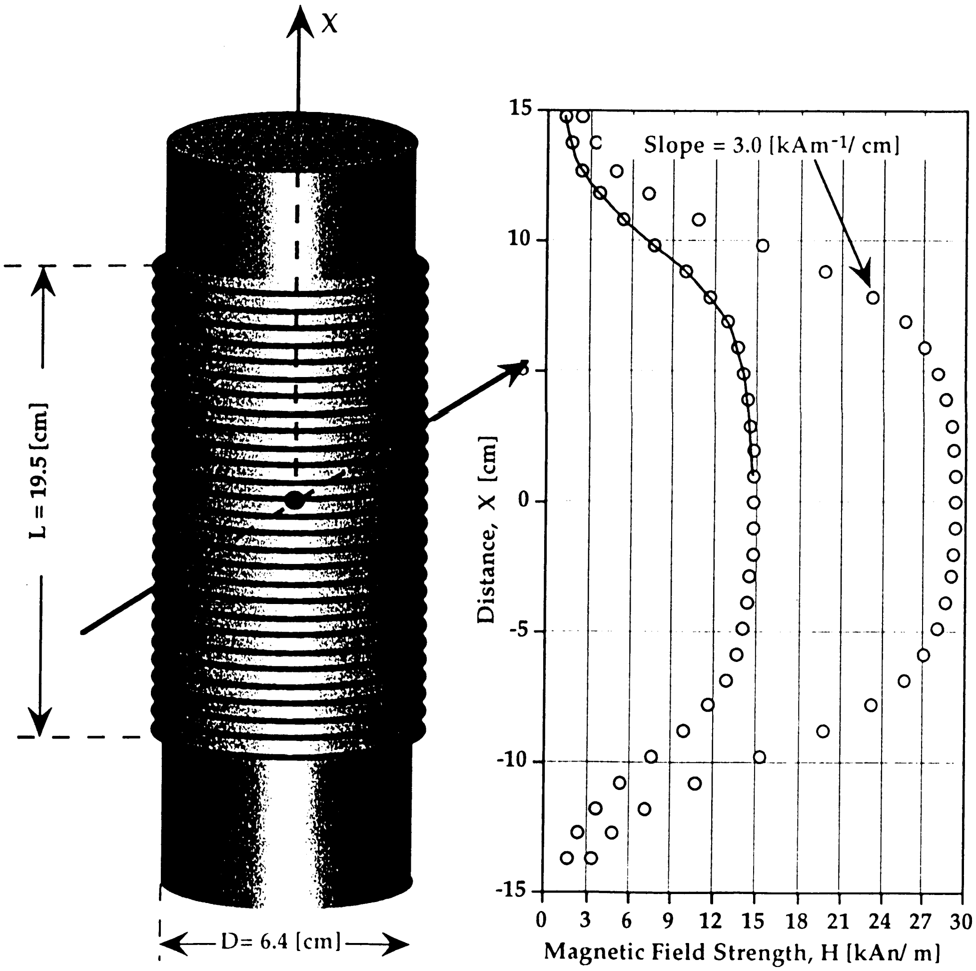

Figure 5. Field strength along the central axis of CCMSFB.

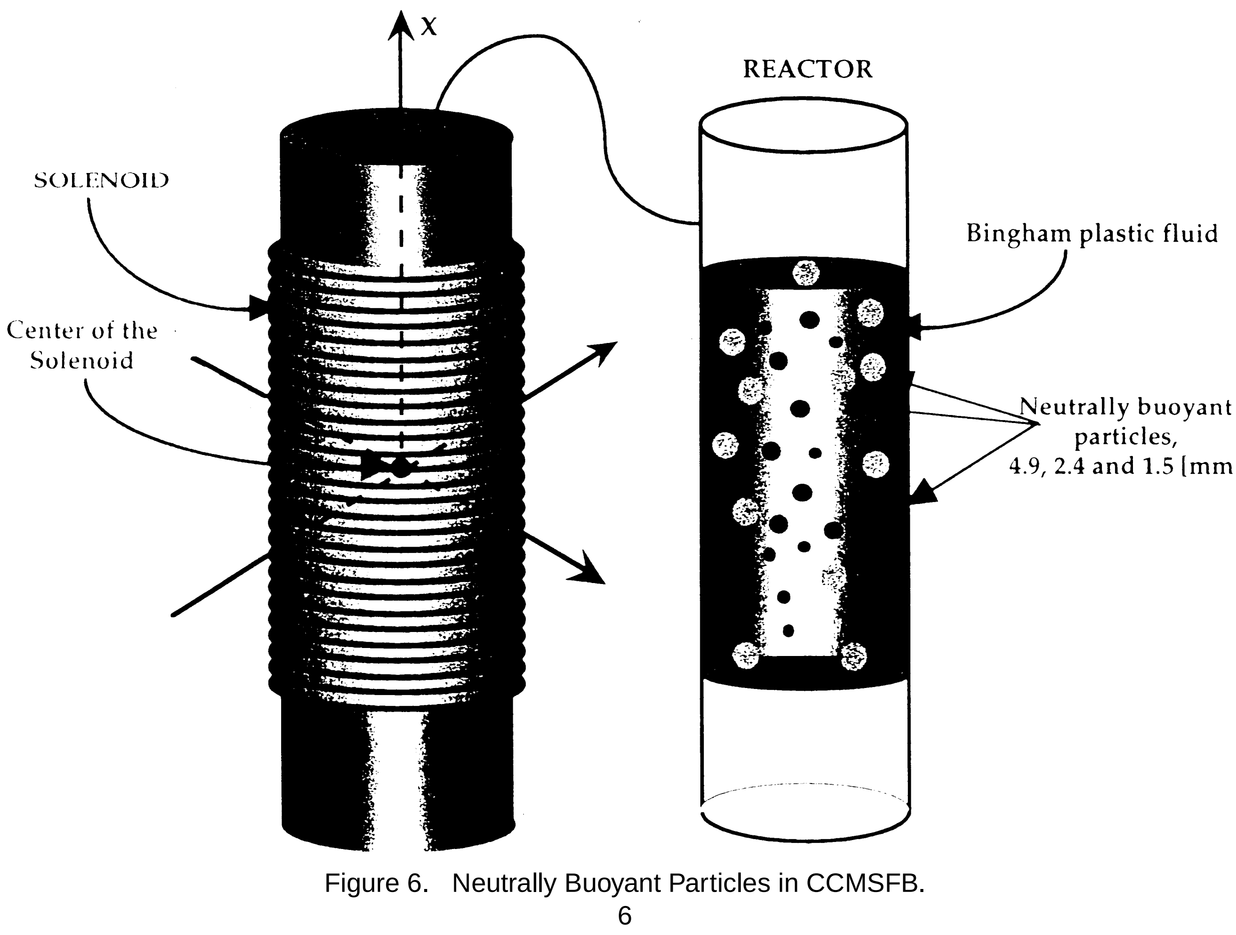

Figure 6. Neutrally Buoyant Particles in CCMSFB.

OPEN COLUMN MSFB WITH CONSTANT GRADIENT MAGNETIC FIELD (CG-MSFB) – The CG-MSFB fluidized bed was designed and assembled for experiments to be conducted under constant gradient magnetic field operating conditions. The CG-MSFB system consists of a fluidization column and a series of seven Helmholtz electromagnetic coils, with DC power supply. Each Helmholtz ring is powered and controlled separately. The apparatus is instrumented with a digital voltmeter and pressure measurement system. The CG-MSFB, illustrated schematically in Figure 7, is part of the closed liquid circulation loop, designed for the solid waste filtration experiments. The column is constructed from a transparent plastic tube with an internal diameter of 4.45 cm (1.75 in) and outsider diameter of 5.08 cm (2 in). The aspect ratio of the reactor is 10:1. The Helmholtz coils consist of 20 turns of 14 AWG copper wire and the pitch between Helmholtz coils is 6.35 cm (2.5 in). The constant gradient magnetic field is provided by adjusting eight independent rheostats. Maximum current and voltage of the power supply is 200 A and 5 V, respectively. However, the system was never operated at power levels greater than 200 W.

In operation, the liquid is pumped from the bottom of the cylindrical fluidization vessel and passed through the fluidized bed of ferromagnetic particles before exiting at the top of the bed. The fluid is then returned to the bottom of the bed for another recycle loop. The fluid flow in this bed can be easily reversed, as needed, for packed bed formation, solid waste filtration, and refluidization processes. During these operations, if desired, the fluidized particles can be held around their equilibrium positions with the help of the magnetic force created in the interaction between the magnetic field and the ferromagnetic particles.

SOLID WASTE FILTRATION

FORMATION OF THE FILTRATION MEDIA USING MAGNETIC FORCES – The efficiency of the Magnetically Assisted Solid Waste Filtration and Gasification System hinges, to a large extent, on the formation of a stratified packed bed of particles of different sizes. A stratified packed bed (Figure 8a) is significantly more efficient in filtering a liquid stream containing suspended waste particles than a random packed bed (packed bed with randomly distributed fluidization particles of different sizes, (Figure 8b) or an uniform packed bed (Figure 8c). The stratified architecture of the packed bed is particularly important when waste particles of different sizes are filtered. If the leading layer of the packed bed filter consists of predominantly large granules it will filter out larger waste particles and will let smaller waste particles be retained in the subsequent layers of the packed bed. In this way the volume of the entire packed bed is engaged in the filtration operation and matting of waste particles at the leading layer is reduced or entirely avoided.

Experiments leading to stratification of particles were performed in two different bed configurations: a) Closed Column MSFB with non-homogenous magnetic field (CCMSFB), and b) Open Column MSFB with Constant Gradient Magnetic Field (CGMSFB).

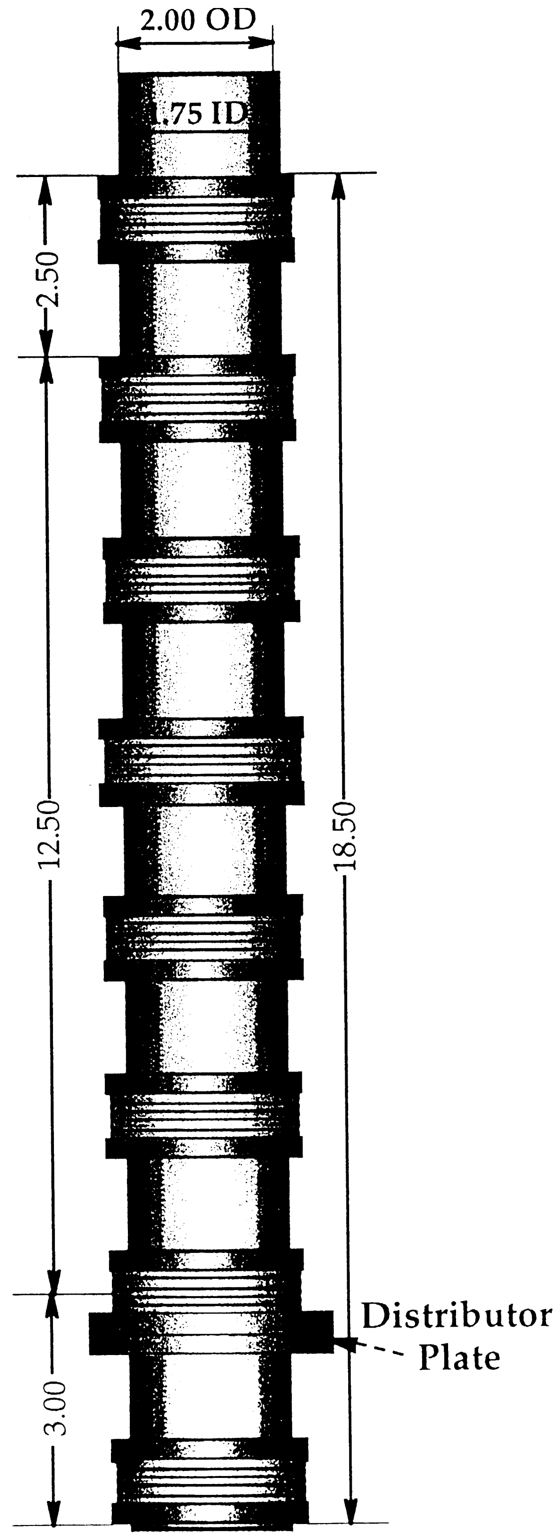

Figure 7. Schematic of a CGMSFB system with Eight Helmholtz Rings.

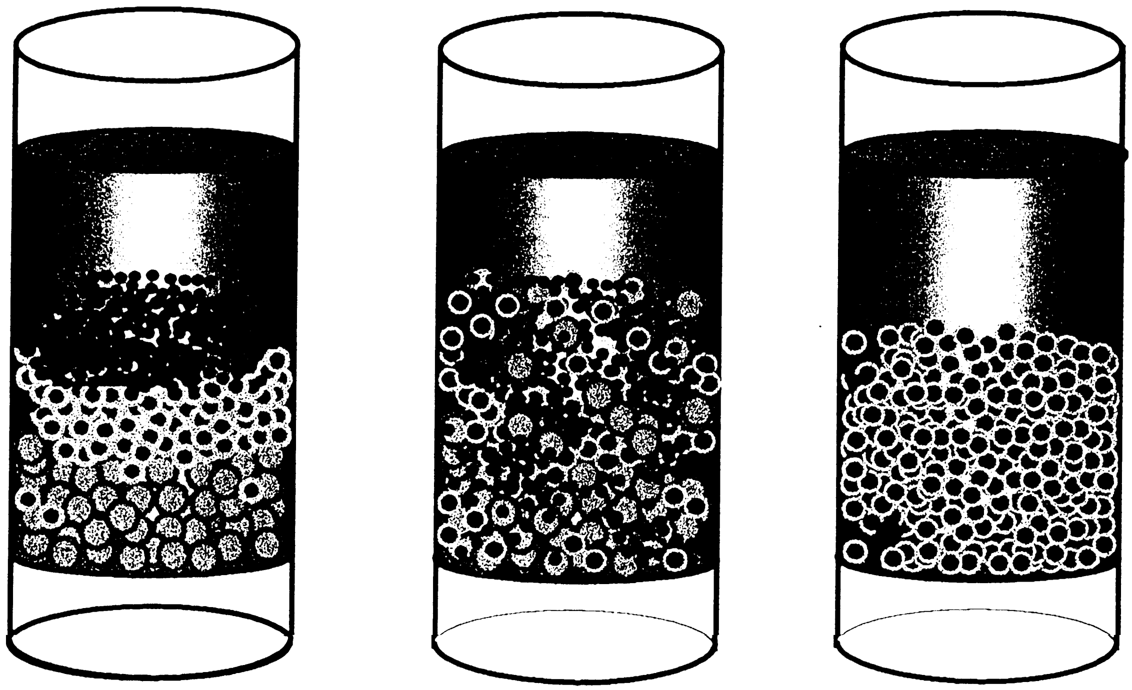

Figure 8. Three Different Types of Filter Media Packing: a) Stratified, b) Random, c) Monosize.

Closed Column MSFB Stratification Experiments – Initial experiments leading to a formation of the stratified packed bed were conducted in the CCMSFB (Figure 6) with neutrally buoyant particles suspended in a weak Bingham plastic fluid. These experimental conditions were used to simulate the microgravity environment in the formation of the stratified packed bed column. It was intended only for a qualitative investigation of particle settling due to the magnetic field gradient.

The column was filled with neutrally buoyant ferromagnetic particles and Bingham plastic fluid, and then closed. Equal amounts of particles with diameters of 1.5, 2.4, and 4.9 mm were placed in the column, so as to occupy 1/4 of the total reactor volume. Under these conditions, to a first approximation, gravity does not have any influence on the motion of particles, since it is compensated for by the buoyancy force (neutrally buoyant particles). Thus, conditions are created for the segregation of particles solely under the influence of the magnetic field.

Experiments conducted in the closed column MSFB clearly demonstrated the particle size segregation effect. Three distinct layers of particles have been formed, with the largest particles (4.9 mm) settling first as the leading layer of the column (closer to the center of the solenoid), with the smallest particles (1.5 mm) settling on the top of the larger ones. However, a smaller fraction of the particles settled to form mixtures of particles of different size. Formation of the stratified packed bed was completed in less than 60 seconds. These experimental results clearly indicate that in simulated microgravity magnetic forces can be used to produce a consolidated bed of filtration media in which the particle sizes are ordered in such a way as to facilitate efficient removal of suspended solid waste.

Open Column MSFB Stratification Experiments (column with constant gradient magnetic field). Measurement of the distributions of particles of different sizes along the height of stratified packed beds were performed in the reactor vessel fitted for the filtration experiments and equipped with Helmholtz rings for the generation of a truly constant gradient magnetic field (CGMSFB) shown in Figure 7. Initially the column was filled with a mixture of equal volumes (≈ 23 cm^3) of three different sizes of ferromagnetic particles.

Experiments were performed without a magnetic field, and with the magnetic field. In 1 g, sedimentation of particles occurs without the presence of the magnetic field due to the density differences between the ferromagnetic particles and water, i.e., Stokes Law sedimentation.

Stratification without Magnetic Force – Particles were vigorously fluidized at a superficial water velocity of U_0=2.3 cm/s. At this velocity, particles appeared to be well fluidized and randomly mixed. Then the fluid velocity was reduced to U_0=1.35 cm/s. At this velocity, particles were still fluidized but under much less vigorous fluidization conditions. Under these conditions, moderate stratification of particles was evident. After 20 minutes the flow was quickly shut off and water was drained from the bed. Particles were picked in layers of 1 cm and their number and size were recorded. Figure 9 shows the volume fraction distribution of each particle size along the bed height in two replicate experiments.

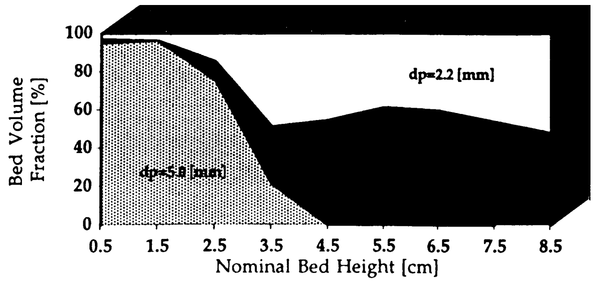

Figure 9. Particle Distribution in Bed without Magnetic Field.

Stratification with Magnetic Force – Again, particles were fluidized at a superficial water velocity of U_0=2.3 cm/s, and the constant gradient magnetic field was turned on. The gradient of the magnetic field was set at -21.5 kAm^{-1}/m. At this superficial velocity and magnetic field strength, particles appeared to be well fluidized, but less vigorously, and randomly mixed. Then the fluid velocity was reduced to U_0=1.35 cm/s. At this velocity, the particles were only slightly fluidized, with those at the bottom of the column where the field strength was the highest almost completely motionless. Under these conditions a very good level of stratification of particles was evident. After 20 minutes the flow was quickly shut off and water drained from the bed. Particles were picked in layers of 1 cm and their number and size were recorded. The resulting volume fraction distribution of each particle size along the bed height from two replicate experiments is shown in Figure 10. Clearly, the magnetic field and magnetic field gradient play an important positive role in the formation of the stratified packed bed. Thus magnetic forces can be utilized to produce a filtration bed with greater efficiency than would occur using randomly packed ferromagnetic granules.

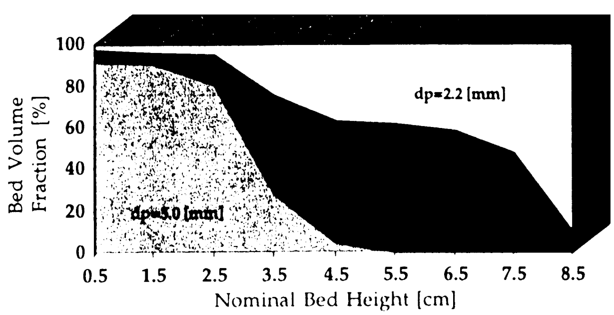

Figure 10. Particle Stratification by Magnetic Field Gradient (-21.5 [kAm^{-1}/m]).

FILTRATION EXPERIMENTS – All filtration experiments were performed in the Open Column MSFB reactor vessel with constant gradient magnetic field (Figure 7). Wheat straw particles were used as the solid waste simulant. Finely cut straw fibers, 2-5 mm in length, were soaked in water for several days. The fiber size was further reduced in a blender. Blended particles were then screened through standard Tyler sieves, and four different screen cuts were separated and saved for the filtration experiments. The size fractions are summarized in Table II.

Table II. Tyler standard screen analysis of the straw particles.

Nominal particle Size [µm] (Blended Straw)	Mash Size (20-28)	Mash Size (28-32)	Mash Size (32-48)	Mash Size (48-100)
	711	503	356	221

A spectrophotometer was used for on-line measurements of the concentration of the straw particles suspended in water by measurement of transmitance at 221 nm. The dry content of straw particles was determined by filtration and drying at 110°C until constant weight. Over 90% of straw particles fell in the size range of 100 - 200 µm, with a median size of 149 µm.

Several filtration experiments were performed using this solid waste simulant. First, a batch of ferromagnetic particles (monosize or mixture), were placed in the reactor vessel and the water recirculation rate, i.e. water velocity through the column, was adjusted to a desired value. At the same time, a previously calibrated and adjusted magnetic field was turned on and the system was stabilized for a few minutes (typically within three minutes). Then, a pre-measured amount of straw particles was introduced in the mixing vessel and the filtration process started. Samples were collected every two minutes and immediately analyzed for solids content. The magnetically stabilized bed of ferromagnetic filtration media rapidly collects straw particulates, enough to substantially increase the pressure drop through the bed. Eventually, the pressure drop increases sufficiently to create a force, opposite to the magnetic force induced by gradient magnetic field, which moves the whole bed from the upstream end to the downstream end of the fluidization column. At this point the whole bed is pressed against the screen at the downstream side of the column, and the magnetic field is no longer required to maintain the integrity of the bed. At this point, the magnetic field can be turned off.

Depending on the size of the field gradient, magnetic field strength, water flow rate, and amount of collected waste particles, the magnetic field may only be needed for a few initial minutes of the filtration operation. The moment at which the stabilized bed is displaced from one end of the column to the other may actually be predetermined by the magnetic field strength. It is not desirable, however, to turn the field off before the bed is firmly fixed in the downstream position, because the bed may loose its integrity and refluidize. The filtration operation is then continued until the pressure drop through the bed reaches the maximum desired or designed value. In the latter part of the filtration process, the matting of waste particles was typically observed at the leading edge of the bed, which was the best indicator of the nearing end of the filtration cycle.

Using these methods, the efficiency of the filtration process in the packed bed of stratified ferromagnetic particles is extraordinarily high. This is evident from the comparison of filtration with and without the magnetic field shown in Figure 11. Typically, a packed bed containing 1,000 cm^3 of ferromagnetic particles retained between 0.5 - 0.7 grams of dry solids from a stream containing a high particulate load (1.5% of dry solids/liter). Filtration efficiency improves with increased magnetic field gradients, as shown in Figure 12. Separation of large particles is very fast, requiring only 30 seconds to complete. The filtration of smaller particles < 150 µm from dilute streams necessarily requires much longer time periods, due to the dynamics of filtration processes (first order exponential decay). It is thus necessary to set a reasonable lower limit on the content of solids in the recycled water before it is returned for another filtration cycle.

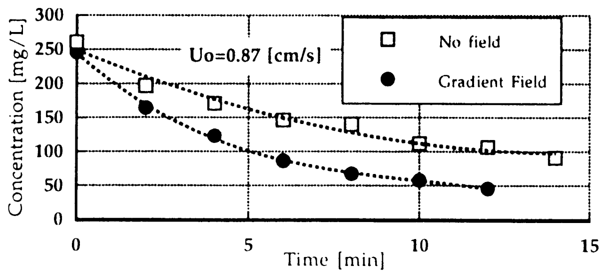

Figure 11. Particle Stratification by Magnetic Field Gradient (-21.5 [kAm^{-1}/m]).

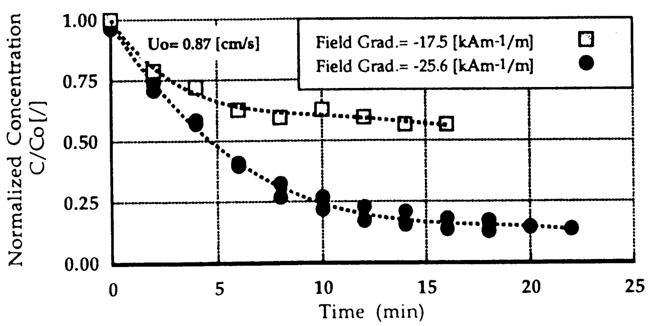

Figure 12. Filtration with and without Magnetic Consolidation of Granular Media.

CONFINEMENT OF FILTRATION MEDIA USING PERMANENT RING MAGNETS – Barium hexaferrite ceramic rings were investigated as a low power alternative for the confinement of ferromagnetic media. Magnetic confinement of iron-nickel media, in opposition to the force of gravity, was achieved using a coaxial arrangement illustrated in Figure 13. With a 7 cm distance between the two sets of ring magnets. The resulting axial magnetic flux densities are shown in Figure 14. The magnetic flux density varies symmetrically about the midpoint between the two sets of magnets. Because the gradient changes sign as the midpoint is crossed, the primary magnetic forces tend to confine magnetically susceptible media between the two sets of magnets. Filtration, combustion, and ash removal experiments were conducted using a 3 cm high magnetically confined bed of Fe:Ni media.

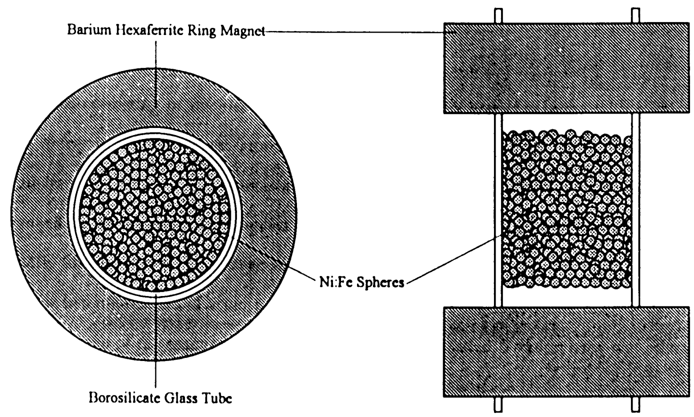

Figure 13. Ring Magnet Configuration for Gravity Independent Confinement.

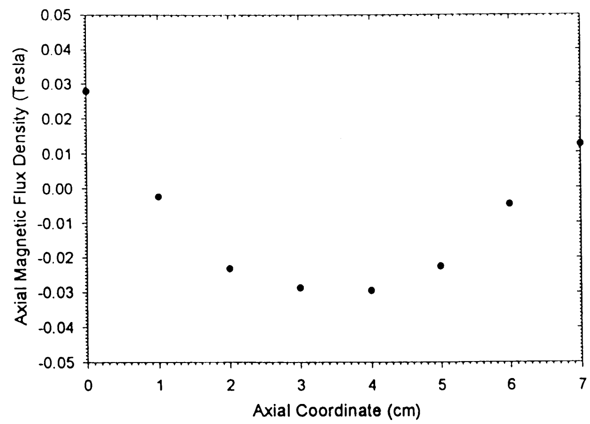

Figure 14. Axial Magnetic Flux Density for the 7 cm Ring Spacing.

A bed consisting of magnetically confined Ni:Fe media was challenged with a 2% (w/w) aqueous slurry of inedible plant biomass (wheat straw), at a flow rate of 50 mL/min. The relatively large bead size, and narrow size distribution of the Ni:Fe media was far from optimal for employment as filtration media, however, sufficient filtration was achieved to demonstrate the concept, particularly for the separation of large solid particles. Small particulate matter (< 0.5 mm) passed through the bed unimpeded. Larger particles were retained. Very large particles (> 5mm) matted on the inflow face of the magnetically confined bed. Solids loaded filtration beds were then used in subsequent combustion and ash removal experiments.

SOLID WASTE COMBUSTION AND ASH REMOVAL

Magnetic confinement, filtration, combustion, and ash removal capabilities were combined into an integrated solid waste treatment experiment using the apparatus illustrated schematically in Figure 15. Wheat straw was removed from a flowing slurry by a magnetically confined depth filter, as described above. With the filtration media still confined, the retained biomass was combusted in a flowing air stream. The Ni:Fe filtration media were then displaced magnetically by changing the positions of the ring magnets, and the remaining ash was removed by a reverse-flow gas purge. The results of this combustion run are shown in Figure 16. Of the 90 mg of dry material initially retained in the depth filter, 11 mg of CO_2 and 20 mg of H_2O were identified in the effluent gas, as determined by a NDIR detector. Condensed tar (10 mg) was collected on a down stream glass wool bed.

Following combustion, the magnetically suspended and consolidated bed was displaced by bringing the two permanent magnet rings together, thereby distributing the ferromagnetic media around the internal circumference of the reactor tube. A gas purge was then applied through the reactor, driving any remnant non-magnetic material (char and ash) into the downstream filter. The material collected as ash totaled 20 mg. The sum of carbon dioxide, water, tar, and ash yielded a 67.8 % recovery. Presumably, the unaccounted 1/3 of the initial mass was converted to a variety of non-detected gases such as CO, CH_4, NO_X, SO_2, etc. Visual inspection of the Ni:Fe media indicated a blue coloring of the material, but showed no evidence of coking or the presence of unreacted material. It is anticipated that in future developments, a combination of pyrolysis, steam-reforming, and combustion reactions will be utilized to achieve complete gasification of the organic constituents of solid waste with minimal formation of problematic species such as NO_X. More sophisticated analytical capabilities will be required at this stage.

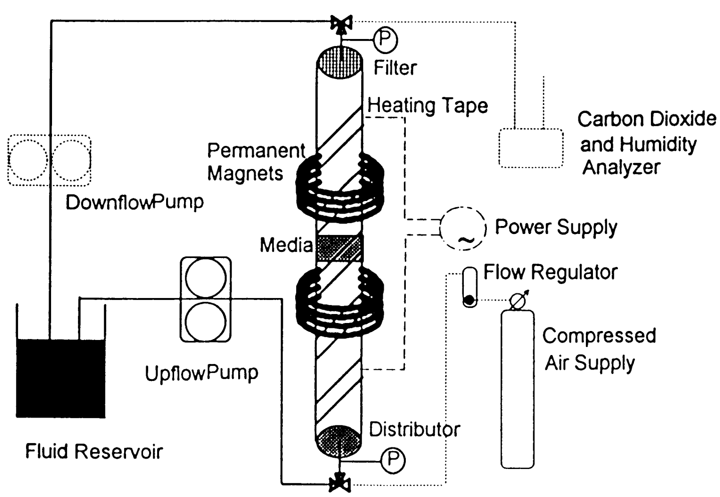

Figure 15. Permanent Magnet based MSFB Test Stand

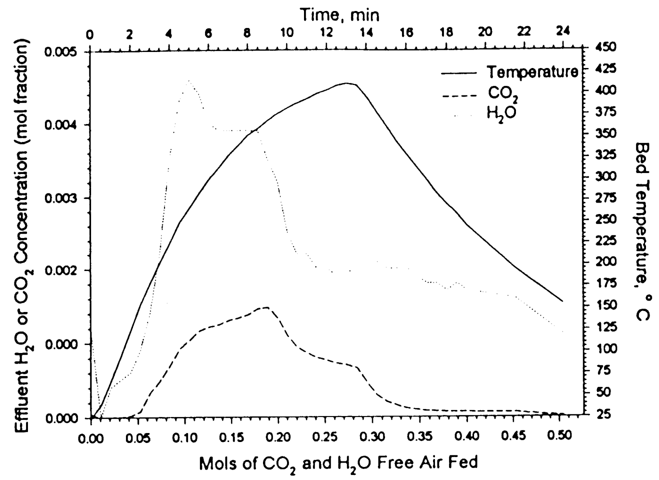

Figure 16. Combustion of Inedible Plant Biomass in Integrated Test.

CONCLUSIONS

The feasibility of the proposed Magnetically Assisted Solid Waste Filtration and Gasification Process has been conclusively demonstrated. Significant advances were made in the preparation of magnetic media, and in the design of both magnetic and reactor systems. Several completely new forms of ferromagnetic materials have been successfully prepared. The required magnetic fields and field gradients were produced using novel electromagnet configurations employing a linear series of Helmholtz coils to produce constant axial magnetic flux density gradients. Permanent ceramic ring magnets were also investigated as a low power alternative for controlling both consolidation and fluidization of magnetic media in flowing gas and liquid streams.

A variety of reactors and gravity independent magnetic manipulation methods were also developed to produce stratified beds filtration media for optimal filtration efficiency. Combustion of retained plant biomass was demonstrated in a magnetically confined bed, with no evidence of coking, char formation, or oxidation damage to the ferromagnetic media. The production of CO_2, H_2O, and gaseous organics was confirmed using on-line instrumentation. Ash removal from the ferromagnetic bed was achieved by magnetic deconsolidation, and gas purge of non-magnetic material to a down stream filter. Given these very encouraging results, it is highly probable that continued development of the Magnetically Assisted Solid Waste Filtration and Gasification technology will lead to the development of more efficient methods and equipment for the destruction of solid wastes originating from manned space flight, particularly with respect to enhanced operational capability for hypogravity and microgravity environments, and the maximal production of useful reaction by-products.

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NOMENCLATURE

F: force (N)
Fv: force per unit volume (N/m^3)
$\hat{\mathbf{i}}$ **:** unit vector
μ**:** magnetic permeability (N/A^2)
μ**o:** free space magnetic permeability (N/A^2)
μ/μ**o:** relative permeability (N/A^2)
***p*:** pole strength (A-m)
***r*:** radius (m)
B: flux density (induction) (T=N/A-m)
H: field strength (A/m)
M: magnetization (A/m)
χ_m**:** magnetic susceptibility (dimensionless)