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BIOREGENERATIVE SYSTEM COMPONENTS FOR MICROGRAVITY

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Abstract

The goal of the class was to design, fabricate, and test prototype designs that were independent, yet applicable to a Closed Loop Life Support System. The three prototypes chosen were in the areas of agar plant growth, regenerative filtration, and microgravity food preparation. The plant growth group designed a prototype agar medium growth system that incorporates nutrient solution replenishment and post-harvest refurbishment. In addition, the unit emphasizes material containment and minimization of open interfaces. The second project was a filter used in microgravity that has the capability to clean itself. The filters are perforated plates which slide through a duct and are cleaned outside of the flow with a vacuum system. The air in the duct is prevented from flowing outside of the duct by a network of sliding seals. The food preparation group developed a device which dispenses and mixes ingredients and then cooks the mixture in microgravity. The dry ingredients are dispensed from a canister by a ratchet-operated piston. The wet ingredients are dispensed from plastic bags through tubing attached to a syringe. Once inside the mixing chamber, the ingredients are mixed using a collapsible whisk and then pushed into the cooking device.

Introduction

During the 1991-92 academic year, the students of the EGM 4000/4001 Engineering Design class at the University of Florida have cooperated with personnel from the National Aeronautics and Space Administration, Kennedy Space Center. The class divided into three groups focusing on alternative growth media, air filtration, and food preparation. Prototype systems were designed, fabricated, and tested. An agar-based growth system, a regenerative filter, and a microgravity batter-based food preparation unit are all examined separately in the following report.

AGAR PLANT GROWTH SYSTEM

Past research on methods of plant growth in microgravity have focused on hydroponic and aeroponic systems of nutrient delivery. Each of these methods of nutrient delivery has distinct advantages as well as unique problems associated with the plant growth process. It was the goal of the Plant Growth Group to design an Agar-Based Plant Growth Unit (ABPGU) that takes advantage of the desirable properties of the gelatinous matrix in addition to minimizing its associated problems.

A major problem facing agar-based growth media is the depletion of nutrients and water over time. Several different types of agar replenishment were tested in order to determine the most effective. These models included the use of a ceramic porous tube to deliver nutrients to the agar matrix, a wick used to draw nutrients from a reservoir, and a nutrient bath which allowed for surface contact between the matrix and the solution. The nutrient bath model proved to be the most effective and the final design of the ABPGU was dictated by this method of nutrient replenishment.

The Plant Growth Group took into account the planting, harvesting, and refurbishing processes, as well as how they apply in an integrated system. Planting and harvesting as individual activities received little focus because of the extent to which they have been studied. However, the activity of holding a seed in place after planting is of crucial importance. The use of agar offers a unique solution to the problem of seed containment. Seeds are contained within the agar matrix and remain stationary via two principles. First, the agar has a tendency to reseal small ruptures made in its surface, such as those ruptures that occur when a seed is imbedded in the agar surface. Secondly, the electrostatic interaction between the water within the agar matrix and the seed coat help to hold the seed within the matrix.

Much attention was focused on a refurbishing process that would be operable in microgravity. Refurbishing the ABPGU presents many challenges. First, plant material above the root line must be detached from the plant growth unit. Then the roots and agar must be cleared from the inside of the growth unit. This necessitates using two complimentary systems.

In order to remove plant material above the root line, the SPGU (Sectored Plant Growth Unit) hydro-refurbishing system, developed in 1991, will be employed (Figure 1). The SPGU involves the use of a refurbishing block that passes along the tracks of a plant growth surface. The refurbishing block has two jets, one of which will act as a water knife to cut the stems of the plants. The other jet is used to remove material from the plant orifices on the surface (Figure 2).

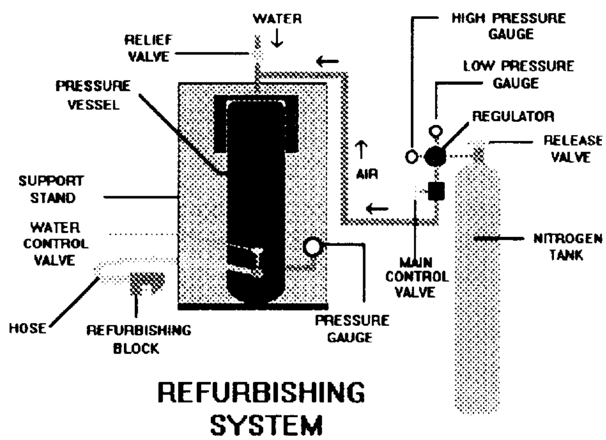

Fig. 1 SPGU Refurbishing System

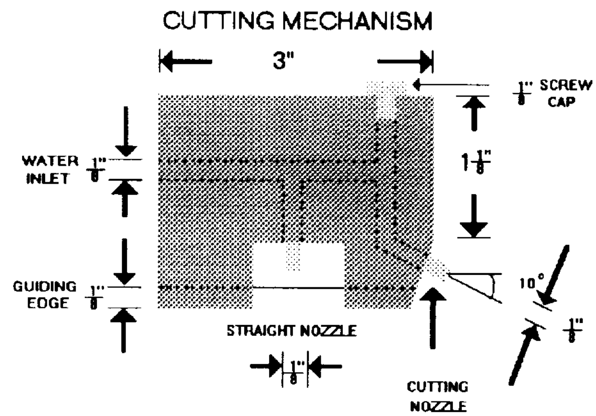

Fig. 2 Refurbishing block and nozzles

Another system must exist to break up the mass of agar and plant material under the surface of a plant growth unit. The used agar must then be removed from the growth unit and transported to the resource recovery station. The growth unit is then prepared for a new cycle of implementation.

Testing of agar refurbishment concepts

Several tests were conducted in order to obtain the most effective agar refurbishment method. Preliminary tests were conducted using a combination of the refurbishing block along with a lateral jet. The water jet's effects were tested on an 8.25 X 13.5 X 3-inch block of agar underneath the SPGU Plexiglas surface. All activities were documented and the following conclusions were made:

1. To break up the agar sufficiently, it is necessary to rotate the jet.
2. A water pressure of 60 psi is adequate for lateral refurbishment.
3. In order to vacuum out the agar, it is necessary for the agar to be near the vacuum nozzle.

Description

The ABPGU consists of a cylindrical Plexiglas container (12" diameter, 12" height) divided into three levels. The levels -- plant growth level, agar matrix level, and nutrient solution level -- are shown in Figure 3.

Plant growth level The plant growth level (PGL) was constructed from a 1/2-inch plate of Plexiglas. A line of holes (seed orifices), 3/8-inch in diameter, was drilled to allow placement of seeds in the agar matrix. Tracks were made on each side of the line of holes to accommodate the refurbishing block (Figure 4).

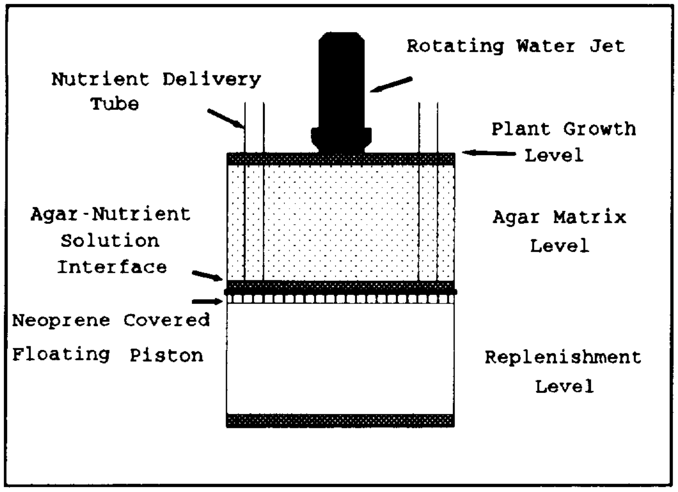

Fig. 3 Side view of plant growth unit

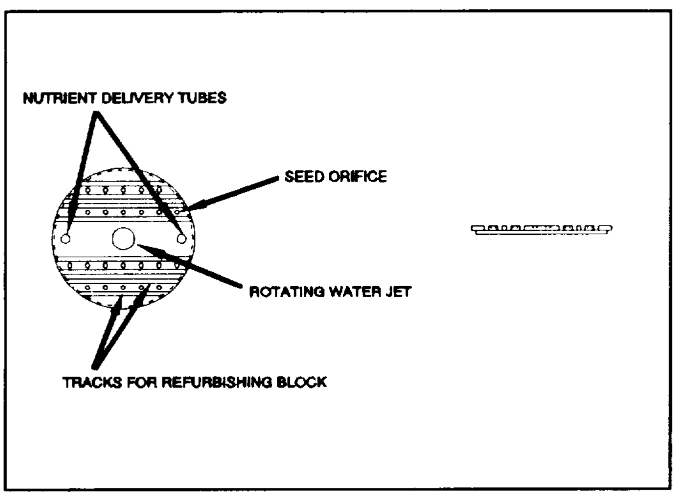

Fig. 4 Top and side view of plant growth level

In order to operate in microgravity, it is necessary to provide a seal at the seed orifices to prevent the agar-slush from escaping from the ABPGU. Several concepts that were considered include:

1. Velcro -- This concept involves a roll of velcro attached to the refurbishing block. As the block runs along tracks on the PGL, the velcro is unrolled and attached. Problems that were considered included the effectiveness of velcro when it gets wet, in addition to the refurbishment of the velcro.

2. Sliding door -- This concept involves a track attached to the refurbishing block. As the block moves across the PGL track, the sliding door is pulled over the plant growth holes. It will be held in place by indentations in the PGL track.

3. Refurbishing hood -- This approach involve using as hood to capture any plant material, agar, or liquids that would be released during refurbishment. A filter could then be used to separate materials either to be reused or transported to the bioreactor. In addition, it is necessary to provide a seal at the plant growth surface during casting. A proposal is to use an additional neoprene-covered piston that would be placed over the PGL during the casting process. It would later be removed to allow for planting.

It may also be possible to incorporate the casting jets into this piston in such a way that the piston would seal the PGL and insert jets through the seed orifices to cast the agar. After the agar had sufficiently hardened, the piston would be removed to allow for the planting process.

Agar matrix level The agar matrix level (AML) contains a six-inch block of agar. The agar matrix is the medium through which the nutrient solution diffuses, providing plant roots with necessary nutrients and aeration. In addition, the matrix is solid, anchoring the plants to the ABPGU.

Nutrient solution level The nutrient solution level (NSL) contains approximately 1.5 liters of nutrient solution that is separated by the agar-nutrient solution interface, a 1/2-inch plate of Plexiglas with holes to allow diffusion of the nutrient solution through the agar matrix.

Testing

Locker-size test module

The locker-size test module (3" diameter, 4" height) was used to test a double-piston concept. Because of its size, it was primarily used in the testing of casting and containment methods.

Casting of the agar

In space, the agar will be injected into the ABPGU in liquid form. During the hardening of the agar, it is important to prevent any leakage through the plant growth surface orifices and the agar-nutrient solution interface. Methods must be considered that will seal these surfaces during agar casting; in addition, other problems include injecting the agar in microgravity, i.e., where will the air displaced by the injected agar go? Because of time and material constraints, the locker-size test module was manufactured to address these problems as described below.

The locker-size test module uses a two-piston concept which is controlled by water pressure (Figure 5). The agar-nutrient interface piston and the floating piston are moved toward the plant growth level (PGL), pressing out any excess air. The agar is then injected, and mechanical pressure is utilized to lower the two pistons evenly (Figure 6).

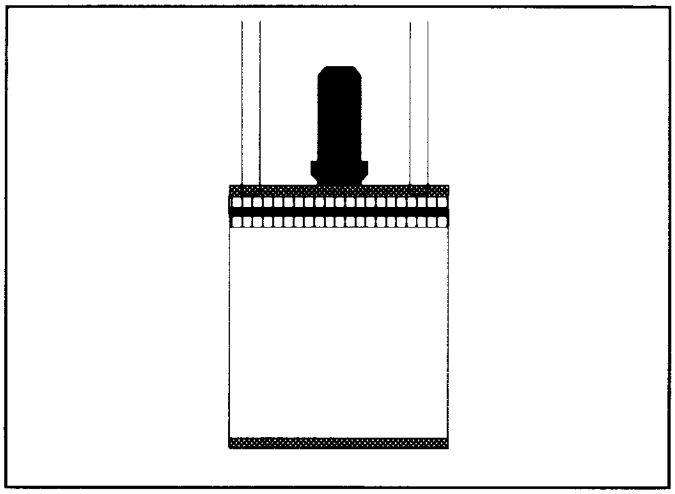

Fig. 5 Unit with both pistons at plant growth level

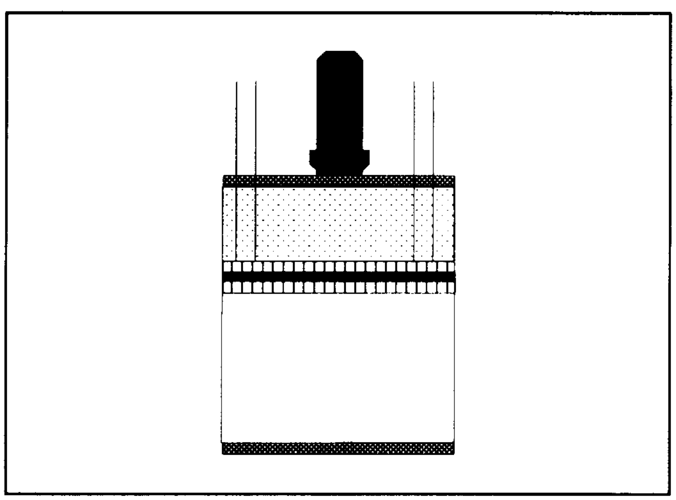

Fig. 6 Unit while agar is being injected

After 100-ml of agar has been injected, the interface piston

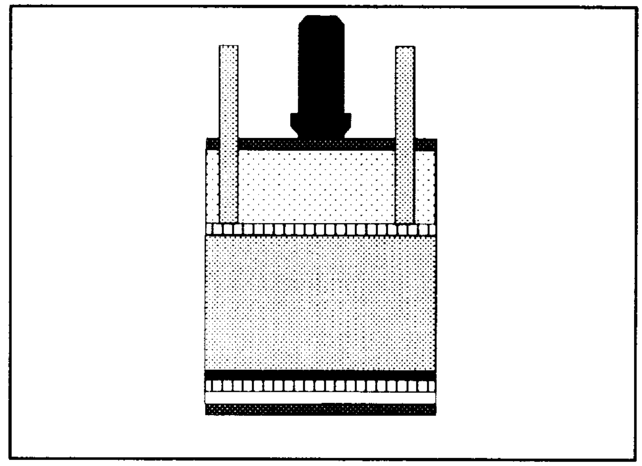

Fig. 7 Pistons separating due to entry of nutrient solution

is immobilized, while the floating piston forms a seal at the interface. Once a seal is formed, the pressure is maintained to hold the floating piston in place until the agar has hardened. The nutrient solution is then pumped in through the nutrient replenishment tubes to return the floating piston back to the base of the NSL (Figure 7).

Testing showed that this method is an effective means of eliminating possible air pockets in the agar matrix. Further testing in microgravity is needed to insure the effectiveness of this method.

Containment A major consideration for the use of the ABPGU in microgravity is the proper sealing of all components and surfaces. The seals provide the mechanism for containment of liquids as well as solids. Testing of the containment of the agar, nutrient solution, and water was done in several steps.

Blue-dyed water was used to examine the effectiveness of the floating piston to seal the agar/nutrient interface. This colored solution was used to provide the pressure necessary to maintain the seal between the neoprene (on the piston's surface) and the agar/nutrient interface. Tests revealed that the piston provided a more than adequate seal. The piston did not allow the mixing of the liquids in the nutrient solution level and the agar matrix level. To demonstrate this fact, liquid was cast into the agar level while the piston sealed the interface. The agar solidified with no leakage into the nutrient solution level and no contamination from the blue-dyed water.

The test for containment of the nutrient solution during the growing process was done once the agar solidified. The test was designed to examine the hindrance of creepage. In the test, capillary tubes were inserted into the agar matrix to simulate the hydrophilic interaction between the water and the plant stem. The results showed that no liquid escaped from the agar, thereby demonstrating the effectiveness of the agar as a seal.

Tests were conducted to explore the concept of using agar as a means of holding the seed until proper root development occurred. In these tests, the seeds were manually inserted into the agar matrix and the orientation of the ABPGU was changed. The tests showed that the agar matrix provides an effective mechanism for seed containment. Tests were run using several different orientations to simulate changes in gravity.

Refurbishment Due to the small volume of the locker-size test module, testing of refurbishment concepts was conducted on the large-scale prototype as described below.

Large-scale Prototype

The large-scale prototype was used to test the refurbishing processes. Containment and casting were hindered by the difficulty of machining a piston with adequately low tolerances for a container of large size.

Containment Water pressure was used to seal the floating piston against the agar/nutrient solution interface. Approximately 2 liters of agar was then poured through the PGL and allowed to harden overnight. However, due to inadequate tolerances of the floating piston, a tight seal was never formed at the interface resulting in a drop in water pressure. This resulted in a small amount of agar flow into the nutrient solution level.

Refurbishment The use of the refurbishing block to cut plant stems and clean the plant growth orifices was tested, and the results were published. Therefore, testing focused on the refurbishment of the agar-matrix level.

As a result of the malfunction of the containment system, testing of refurbishment was conducted using primarily the agar matrix level and plant growth surface. The floating piston was permanently positioned to form a seal at the interface, and the agar was recast and allowed to harden overnight. Then refurbishment was conducted using the 360° rotating water jet to break up the agar and a wet-dry vacuum to extract the agar-water mixture.

Problems occurred because the wet-dry vacuum did not extract the water at a fast enough rate; hence, the agar matrix level overflowed with water. In addition, the agar used in testing was of a higher concentration than would normally be used, resulting in difficulty for the rotating water to break it up. To compensate, the flow rate of the rotating jet was reduced and the power of the vacuum was increased. These adjustments corrected the problems and demonstrated adequate refurbishment of the agar matrix.

Conclusion

At the outset of the project it was decided to focus primarily on the aspects of replenishment, containment, and refurbishment. It was decided that the actual growth of plants in agar would not be studied in detail due to the abundance of studies already conducted.

The first generation large-scale prototype demonstrated that the agar matrix could be replenished. In addition, containment of liquid and solid materials was shown. The agar proved to be an effective mechanism for seed containment and inhibition of creepage. Problems with the casting process were envisioned with the first generation prototype. Also, problems with achieving adequately low tolerances occurred as a result of the machining process and due to the increasing size of the materials used.

The second generation small-scale prototype was designed and fabricated to deal with the problem of uneven agar casting in microgravity. Testing of this prototype, when subjected to changing gravitational vectors, proved the concept to be an adequate means of even agar casting.

REGENERATIVE PARTICLE REMOVAL SYSTEM

A closed loop life support system requires many interfaces between mechanical and biological systems. The air-handling system in a plant growth chamber requires cleaning interfaces to remove solid contaminants from the air stream. This cleansing allows efficient circulation. The removal of particles from the atmospheric loop is also a necessary process for dehumidifying equipment to operate properly. This project focuses on a regenerative air cleaning system that will remove solid particles from an airstream.

A regenerative particle removal system is one which is able to stay near its optimum efficiency at all times. Whenever the efficiency drops below some threshold, a cleaning operation will return it to its original condition. This type of system will not use replacement filters.

The concept of a regenerative air cleaner satisfies a need for long-term space applications. This concept could be implemented in the design of extra-terrestrial bases and in extended duration space travel, or in any system where extra space or replacement materials are in short supply. Over an extended period of time, a regenerative cleaner can justify its initial cost and weight through its reusability. By reducing maintenance needs, it may also provide greater long-term reliability.

A regenerative air cleaner can eliminate the use of replaceable mesh filters and save on maintenance and storage space. The use of replaceable or throw-away filters on a long-term space mission requires an abundant quantity of substitutes and storage space. The time and energy costs of the replacement and disposal activities would probably be quite high. Storage space for used filters must also be provided. A regenerative system negates these replacement factors and fits a closed system.

In the fall of 1991, this group determined the criteria for an air cleaning process and apparatus. An overall design consisting of removable filter plates was suggested. Along with this conceptual design, alternative concepts and methods were evaluated. These included organic filters, rotary filtration, electromagnetic field, and a sensor that determines when the filter needs cleaning.

Prototype Design Description

Through matrix evaluation and objective decision-making, a final system design was selected. The design utilizes a rectangular duct with rectangular filter plates that fit together to form a matrix. The plates are perforated sheets of steel which are oriented perpendicular to the airflow direction. These plates will be able to slide through the duct and be cleaned outside of the airflow (Figure 8). This method will allow cleaning without interrupting the air circulation.

Each plate slides through apertures on two opposing sides of the duct. As the plate moves through the duct, a brush and scraper blade free the particles from the plate surface. The brush-scraper combination is attached to the nozzle of a vacuum hose. Loosened particles are drawn into the vacuum

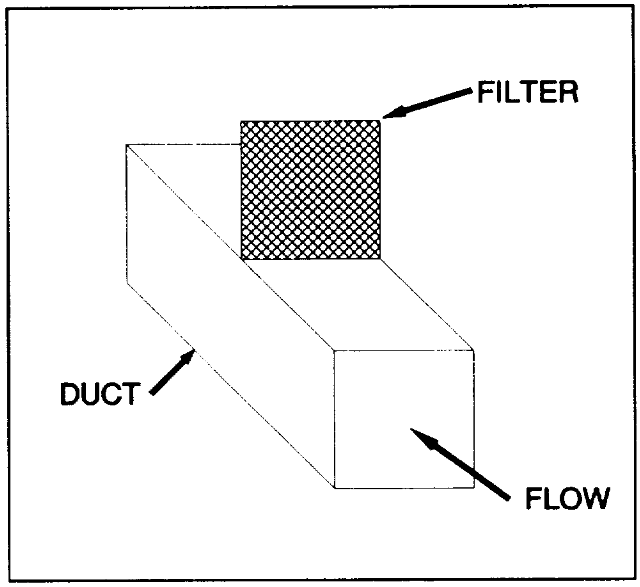

Fig. 8 Design concept schematic

system and collected in a nylon bag. This cleaning procedure is performed outside of the duct.

The apertures in the duct walls are governed by sliding seals. These seals prevent leakage during flow operation and provide clearance for plate movement when necessary.

Prototype Construction

Perforated plates

Perforated screens were available from a variety of retail sources. Twenty-five square feet of perforated steel was purchased from the Harrington and King Perforating Company. The sheets are 0.6 mm in thickness, have circular holes which are 1.0 mm in diameter, and have 45% open area. These specifications were chosen to maximize the filtering efficiency while retaining an adequate flow rate.

The raw sheeting was cut into rectangles which measure 20 x 6 inches. A rectangular mild steel frame has been welded to each end of each plate. This provides an attachment point for the strings which will move the plates.

Duct

The unassembled steel duct was manufactured by Thompson Sheet Metal. The duct has a 6 inch x 8 inch cross-section, a length of 3 ft, and six pieces to allow for plate apertures (Figure 9). The fabrication of the duct allows the six side pieces to be snapped together. This has enabled the sides to be worked on separately for fastening seals, channels, and other mechanisms. In addition to the six sides, L-shaped channels were machined and attached to the inside of the duct to guide the movement of the filter plates.

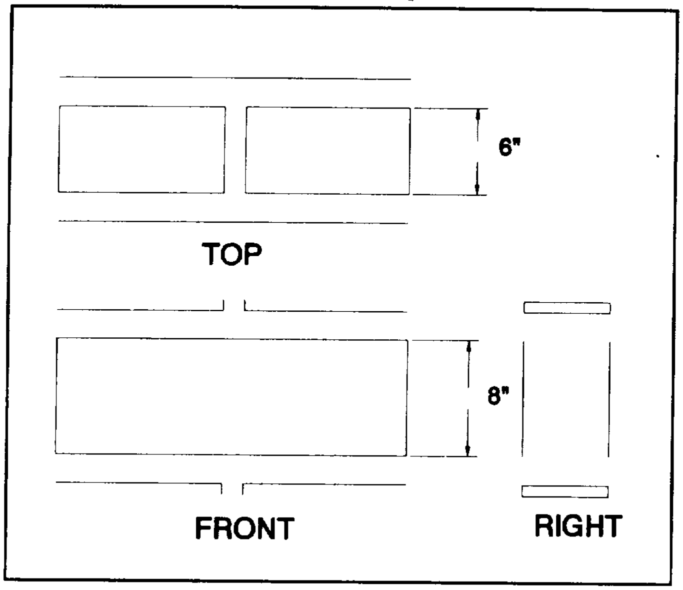

Fig. 9 Unassembled duct

Plate movement

The plates are moved through two openings in the duct cross-section and guided by channels mounted on the duct walls. Two electric motors pull the filter plates back and forth by a cord and pulley system (Figure 10). The figure shows a schematic configuration for one plate.

The system uses two 500 mA motors turning at 40 revolutions per minute. Driving the plates with these motors causes the plates to move at a rate of 1 in per second. The motors are connected to the plates with multi-stranded Kevlar fiber. Kevlar's material characteristics assure high test strength and small stretch allowance. The small diameter and flexibility of the fibers have allowed adequate interfaces with the pulleys and spindles.

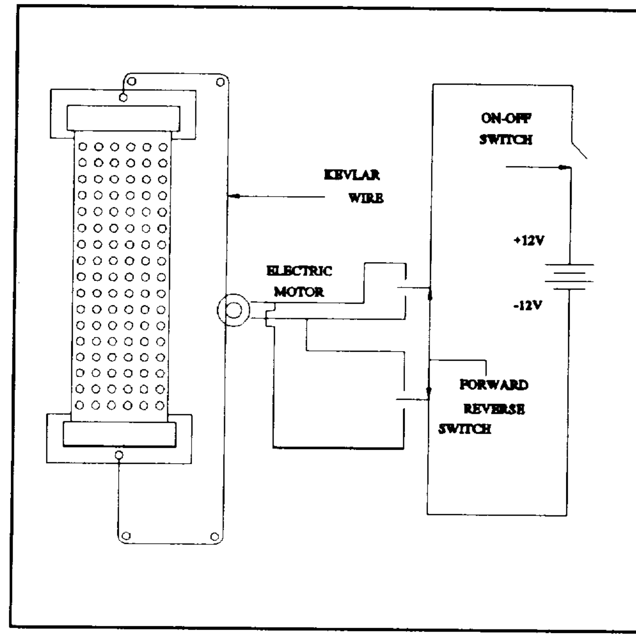

Fig. 10 Moving plate schematic

Inter-plate Seals

Six seals prevent escaping airflow between the plates and the duct wall. In an implementation with a larger number of plates, the number of seals required is $2(n + 1)$, where n is the number of plates. Each seal is a strip of aluminum covered with a plastic coating. These strips run across the filter plates from one edge of the duct opening to the other. In the closed position, each strip fills the gap between two plates. The strips are able to rotate around their long axes. A 90° rotation, where the seals become parallel to the plates, opens the aperture and allows the plates to move (Figure 11). In addition to rotation, the seals translate along the duct edge. By moving the vertical seal up against the non-moving filter plate, space is generated for debris to pass out of the duct.

In this prototype, the seals are manually activated. A short wire on each end of each seal is used to force the rotation and translation. This is a process which could be easily automated, but this automation was not feasible within the time constraints of this project.

Cleaning system

A filter plate cleaning system has been developed to integrate with the duct. It consists of a vacuum nozzle

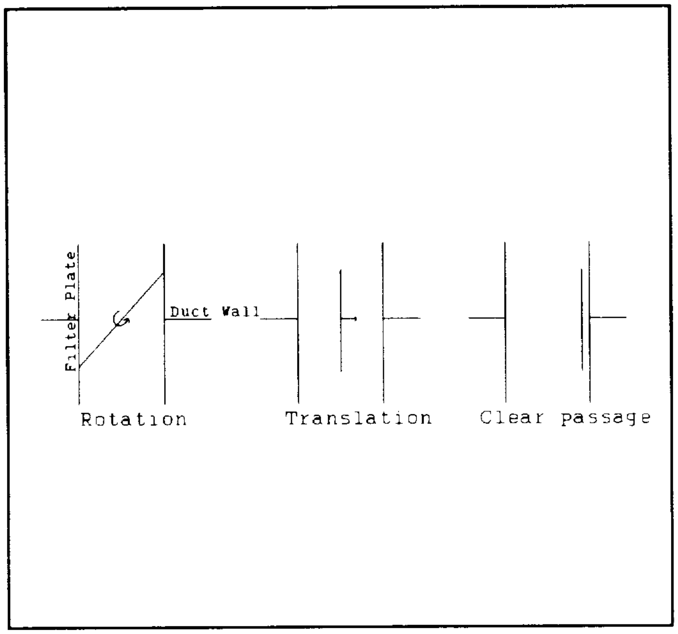

Fig. 11 Cross-section of seal placement

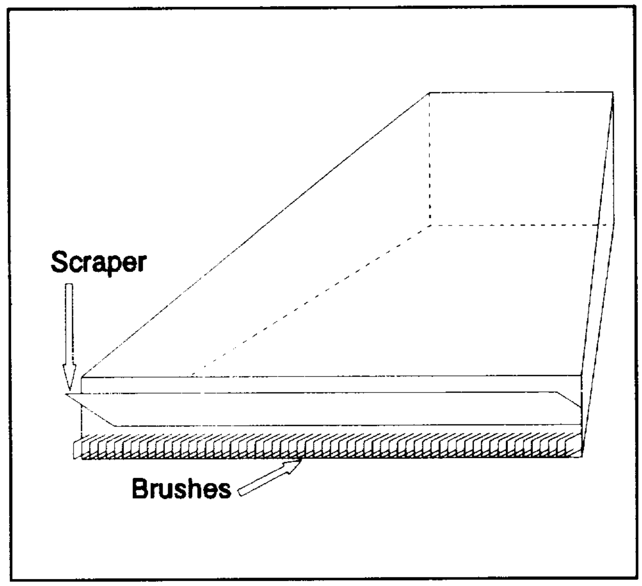

Fig. 12 Vacuum nozzle

equipped with a brush and scraper combination (Figure 12). As a dirty plate moves through the duct aperture, the brush and scraper loosen debris. The debris is then gathered and removed by the operating vacuum.

The vacuum nozzle is a hollow wedge made of mild steel. The entry area is 0.875 x 6.0 inches. The exit area is 2.5 x 2.5 inches. In order to make the cleaning system more effective, the flow velocity across the plates has been maximized. Moreover, the distance between the nozzle and the plates has to be very small. Two vanes inside the nozzle help to regularize the flow and ensure that the flow is the same at all points across the nozzle entrance. A flow meter was used to measure the flow velocity at the nozzle exit. It is worth noting that the velocity decreases rapidly away from the nozzle. It decreased by almost one-half at 0.25" from the nozzle.

Prototype Testing

Filtration testing apparatus

Efficiency of the system prototype was determined with the use of the following procedures. A blower (115 watts, 4 x 5.25-inch exit) was attached to the beginning of the duct to produce airflow. The interface between the duct and blower was sealed to prevent backwards flow. Test particles (sawdust) were inserted directly into the blower intake. At the far end of the duct, a fine mesh of nylon was attached to catch unfiltered particles. The same nylon material was used to recover vacuumed particles from the cleaning system. The vacuum was driven by a 1.5 hp wet-dry vacuum apparatus. Mass readings of dust entered, dust cleaned, and dust exited were recorded.

Pressure and flow rate data were also taken during operation. Static pressure readings were taken from holes in the duct at 9 inches before and after the plates. A manometer accompanied by a pitot tube yielded the measurements. The flow rates were taken at the same position as pressure readings with a hot wire anemometer. The prototype was also tested for microgravity effects by altering the gravitational position vector and observing any changes in data. This was achieved by operating the system 90° from its original position on the longitudinal axis. An orientation of 180° rotation was not necessary due to the symmetry of the design.

System efficiency

Particle removal effectiveness was determined by evaluating the efficiency of the filter. Efficiency discussions require the following definitions.

E = Filter efficiency
TP = Total amount of particulate matter which flows through the duct in a given time interval, by mass.
FP = Amount of matter which is removed from the flow by the filter, by mass.
UP = Amount of uncaught matter which passes through the filter, by mass.

$$TP = FP + UP$$

$$E = FP / TP = FP / (FP + UP) = 1 - (UP / TP)$$

The filter efficiency was calculated by measuring the mass of particles which was able to pass through the filter. The mass of the nylon collection bag and its contents was determined before and after each filter test. The difference in the two masses is the value UP, the uncaught particle mass.

Test results

Flow rates and pressures of the system were taken periodically during flow operation and averaged. At a flow rate of 500 fpm exiting the blower, the pressure drop across the plates was .02 in H_2O. A higher flow rate of 600 fpm was achieved by combining the existing blower with a 1.5 hp wet-dry vacuum. This increased flow rate yielded a pressure drop of .053 in H_2O. The measured flow rate of the vacuum system was 3400 fpm at the nozzle entrance.

The system was checked for efficiency with two data runs in the upright position and one in the rotated position. Table 1 summarizes these three tests with values of dust entered, dust exited, and efficiency percentage. The efficiency presented here is in respect to the total dust mass entering the system. Tests one and two are in the upright position and test three is the rotated orientation.

Table 1 Efficiency testing

	1	2	3
Dust entered (grams)	5.9	18.2	16.6
Dust exited (grams)	2.2	2.3	2.7
Filtration efficiency (%)	63	88	84

The prototype was also tested for cleaning success. Three data runs were taken in similar conditions as the efficiency recordings. Table 2 displays the three tests and the values of dust entered, dust recovered, and percentage amount of dust recovered from total mass. Tests one, two, and three correspond to the same orientation as in Table 1.

Table 2 Cleaning system testing

	1	2	3
Dust entered (grams)	8.1	23.4	8.0
Dust recovered (grams)	0.9	4.8	2.8
Percent recovered (%)	11	21	35

Leakage

Flow leakage during system operation was minimal when the seals were in the closed position. However, when the seals opened to allow plate movement, flow and particles leaked out of the duct. Extensive particle leakage was observed through the lower seals when the system was in its upright position. The loss of recorded dust mass is attributed to this leakage. Another cause of particle leakage is the multiple sizes of the dust particles. Pieces smaller than 1 mm are expected to leak through the perforated plates. This fact shows that the mass readings may not be fully representative of the system's potential because some of the escaping mass was too small for the filter. The use of mixed particle sizes may have attributed to the low cleaning percentages and filter efficiency.

A FOOD PREPARATION DEVICE FOR MICROGRAVITY

On extended space missions, it will be necessary to produce foods to satisfy the crew physically and psychologically. The production of these foods will be limited to those ingredients produced by the plant growth units on board or from supplies brought from earth.

The objective of this project is to design and manufacture a device for food preparation in microgravity. The project focuses on producing a variety of cooked foods containing similar ingredients. After researching the different foods that could be produced, the project team decided to focus on the preparation of pancakes, waffles, and other flour-based foods.

The food preparation device for microgravity was completed in three phases. Phase I consisted of the design and testing of a mechanism which dispenses wet and dry ingredients in measured quantities. This led to Phase II of the project which entailed mixing the ingredients into a batter substance. Phase III completed the hardware portion of the project by yielding a mechanism which, when integrated with the first two phases, cooked the batter.

Developed Ideas

Dispensing

Several types of dispensing mechanisms were investigated for both the wet and dry ingredients. The main considerations for a dispensing design include prevention of leakage, accurate measurement of ingredients, and control of ingredient flow. A matrix of the various concepts considered and a discussion of the results accompanies this section. Illustrations of the dispensing mechanisms considered are shown in Figure 13.

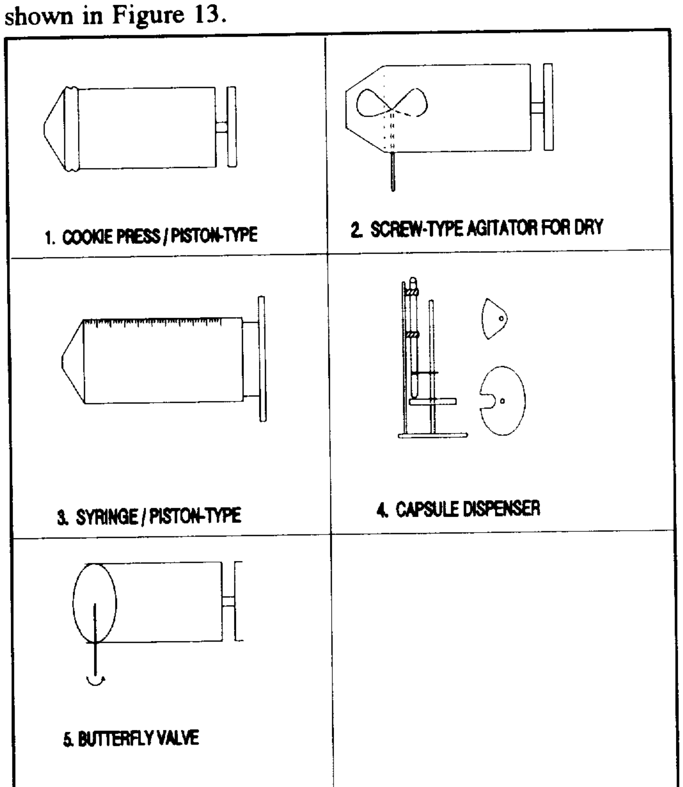

Fig. 13 Ingredient dispensers considered

Experiments Performed The first experiment involved the use of a cookie press to simulate a piston moving dry and wet ingredients. Dry ingredients will not move unless the exit diameter is the same as that of the container. The flour (the primary constituent of the dry ingredient mixture) became packed as it was displaced toward a smaller area. The wet ingredients flowed easily with piston displacement, but accurate measurements were hampered since the flow did not immediately cease when the displacement force was removed.

The next experiment involved the use of a screw-type mechanism. This was used to agitate dry ingredients at the dispenser exit and to eliminate packing tendencies. Although the dry ingredients moved well, this mechanism requires the implementation of an accurate measuring device. In addition, the agitating mechanism adds mechanical and automation complications.

The possibility of eliminating dry ingredients was considered by preparing a mixture of flour and milk in the piston-type device. This reduced the bulk of dry ingredients dispensed, but additional dry ingredient mixing (i.e., sugar and baking powder) is still required. Another drawback is that the amounts of some ingredients vary according to the desired recipe.

Another piston-type experiment was performed using a syringe and a check valve to dispense and accurately measure wet ingredients. The results were favorable since the flow of liquid ingredients ceased immediately, and no leakage was detected.

In addition to the mechanisms mentioned above, dissolvable capsules were considered for the dispensing of baking powder. The capsules held one-half teaspoon each and dissolved almost immediately when immersed in hot liquids. They did not, however, readily dissolve in cold liquids. Mechanisms for dispensing the capsules were investigated. A model was assembled, and it performed favorably, but further modification would be required for use in microgravity.

Another option for dry ingredient dispensing is the use of containers filled with pre-mixed portions of the dry ingredients (i.e., flour, sugar, and baking powder). These individual containers would hold a mix for pancakes, waffles, and other dry mixes. The preparation of these containers would take place in the food processing area. Each container would contain enough dry ingredients for one or two recipes. For example, one recipe of pancakes is equivalent to three eight-inch pancakes.

Mixing

Six mixing mechanisms were examined. They included a blade-type mixer, a kneading-type sealed-bag mixer, a magnetic stirrer, a high-speed rotation apparatus, a shaker, and a collapsible whisk. Initially, the ingredients were mixed by conventional rotary mixer, and the resulting batter was used as a control mixture. The resulting batters and control mixture were then cooked on a conventional skillet to compare their texture and flavor. Illustrations of the mixing mechanisms considered are shown in Figure 14.

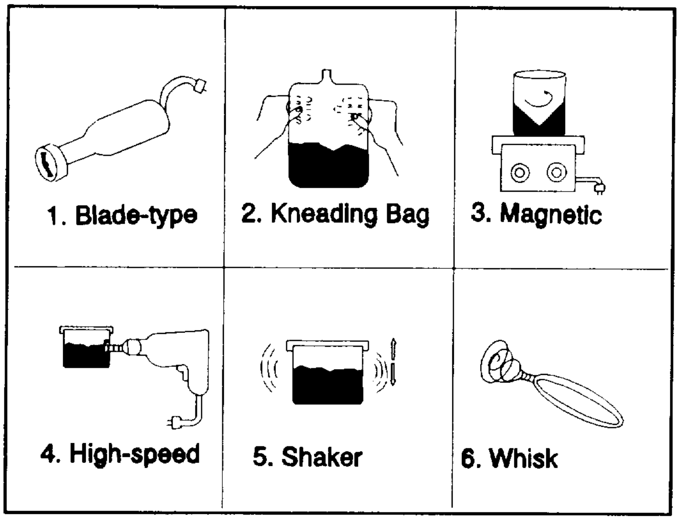

Fig. 14 Mixing mechanisms considered

Experiments performed The blade-type mixer quickly produced a smooth batter and a cooked product comparable to the cooked control mixture. The mixing time required was approximately 30 seconds. This time is shorter than that using conventional means which had a mixing time of approximately one minute. In microgravity, an additional mechanism would be required to oscillate the blade through the batter for thorough mixing.

The mixing of ingredients using the kneading-type sealed-bag method produced a lumpy batter in three minutes mixing time. However, the taste of the cooked product was comparable to the cooked control mixture.

A magnetic stirrer failed to mix the ingredients thoroughly because it could not overcome the viscous force of the batter as dry ingredients were added. For this reason the magnetic stirrer was discarded as a mixing option.

The high-speed rotation device consisted of a container adapted to rotate with a shaft connected to a power drill. The device yielded a lumpy batter unusable for cooking.

The shaking of ingredients in a container produced a batter comparable to that of the kneading method. However, this method would require complex mechanical manipulations.

A collapsible coil whisk was modified to fit a shaft and was used for mixing. The whisk reduces the number of mechanisms required because the coil extends the length of the mixing chamber, thereby eliminating the need for an oscillating mechanism. In contrast, the blade-type mixer required an oscillating mechanism to mix the ingredients into a batter comparable to the control mixture.

Final Design

Overview

A constant area container with pre-mixed ingredients is used for dispensing the dry ingredients (flour, sugar, and baking powder). The dry ingredients are moved into a mixing chamber using a ratchet system. The wet ingredients (milk, eggs, and oil) are contained in individual bags. A syringe/check valve assembly is used for dispensing the wet ingredients from the bags. Once in the chamber, the ingredients are mixed with a collapsible coil whisk. A piston mechanism is used to move the batter out of the mixing chamber and into a cooking unit. The cooking unit has removable hot plates so that foods of different shapes can be cooked. A setup of the final design is illustrated in Figure 15.

Setup

The dry ingredient ratchet container, the batter exit port, and the liquid ingredient insertion port are located at one end of the mixing chamber. The whisk-mixing apparatus and piston assembly are attached at the other end as depicted in Figure 15.

The mixing chamber is a Plexiglas cylinder machined to 4.75 inches in length and 3.765 inches inside diameter. The piston mechanism, also of Plexiglas, has an outside diameter of 3.760 inches. An AC motor for the mixing mechanism was modified from a common hand-held mixer.

Operation

Initially, the piston and whisk are at one end of the chamber. As ingredients are inserted, the piston moves back, the whisk extends, and the ingredients are mixed into a batter. The piston and collapsible whisk allow the chamber to stay airtight, thus eliminating excessive air in the batter.

Seals and Close-off Mechanisms

Since one of the primary design specifications is to

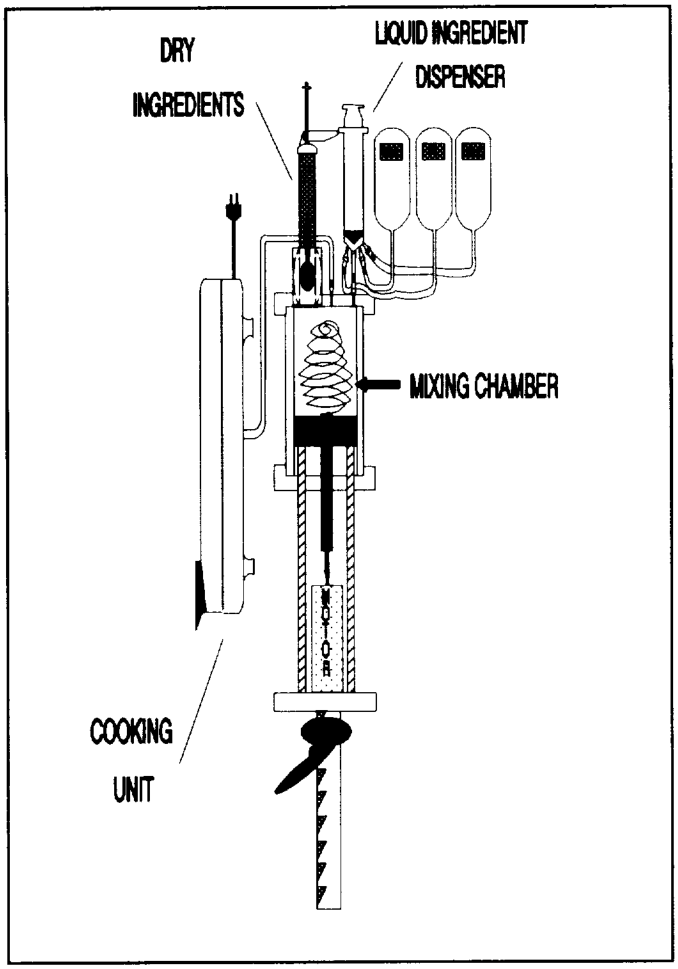

Fig. 15 Final design

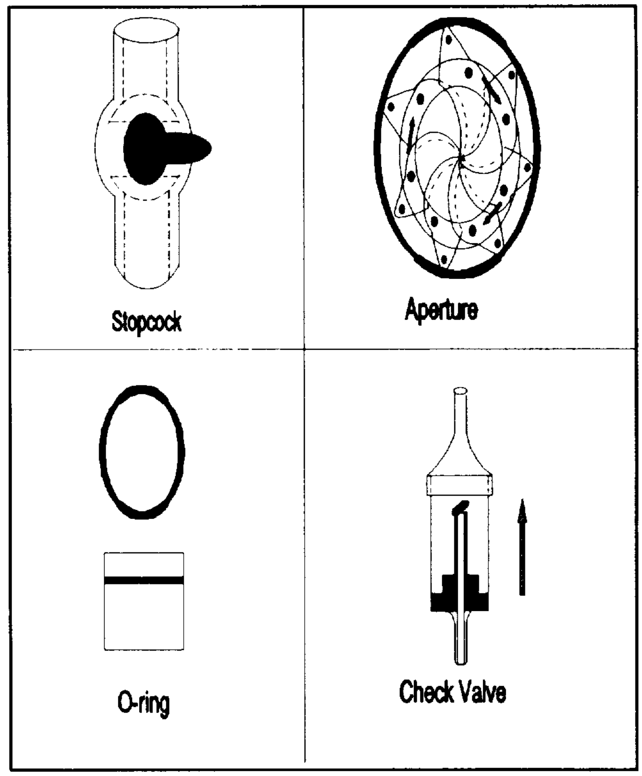

Fig. 16 Seals and close-off mechanisms considered

prevent leakage, a variety of seals and close-off mechanisms were considered. Close-off mechanisms were investigated for the dry ingredient dispenser. Several concepts for leak prevention between the piston and mixing chamber were examined. A means to prevent backflow of wet ingredients in the dispensing tubes was explored. These seals and close-offs are depicted in Figure 16.

Dry Ingredient Close-off The close-off mechanism between the dry ingredient dispenser and the mixing chamber is necessary so that the dry ingredients can be restocked. A stopcock and an aperture system (such as a camera lens shutter) were investigated.

A canister of flour was attached to the stopcock. The stopcock was opened, the flour was displaced, and the stopcock was closed. The flour did not hinder the closing of the stopcock, and the entire procedure was leak-proof.

For the purpose of preliminary experimentation, a canister of flour was attached to an aperture system. Not only did dry ingredient particles imbed themselves between the intricate petals of the device, but the slightest amount of moisture also caused the plates to remain open. Even though the sticking of the plates could be corrected, problems with leakage would still be present.

Piston Seals Another area of potential leakage is in the clearance between the walls of the mixing chamber and the piston. To prevent leakage, incorporating an O-ring, supplying oil as a hydrophobic repellant, and using a low tolerance with no seal in the design were considered.

A piston with an O-ring was manufactured from a polyvinylchloride (PVC) pipe. This was done to study the manufacturing processes involved in machining pistons with O-rings. From these experiments, it was concluded that the manufacturing of a piston-seal assembly requires very exact machining of the piston and chamber. This exact machining was not feasible because of time constraints and lack of experience.

In another experiment, a film of oil was applied between the piston and chamber to repel liquid ingredients and lubricate the piston. However, this method did not provide the close wall tolerance necessary to expel most of the batter.

Finally, the elimination of a seal in the chamber assembly was considered, and a round piston and matching chamber were manufactured. Since the tolerance was maintained to within 0.005 inches, no leakage occurred while the piston was kept stationary. Further experiments were performed, and it was determined that the level of leakage was negligible.

Pinch Valves Tubing from the wet ingredient dispenser was mailed to Bio-Chem Corporation to determine the gap size required for the pinch valves. Since each pinch valve costs $50 and three pinch valves are required, it was determined that the cost was not justified when the tubes could be closed-off manually. For this project, roll-off pinch valves are used to close off the tubes when not dispensing ingredients at a given time.

Experiments were performed with one electronic pinch valve and three roll-off pinch valves. Although the electronic pinch valve provided positive results especially in the area of automation, the cost restricted the use of these devices. Manually operated roll-off pinch valves provide positive results and are incorporated in the final design.

Seals A stopcock is used in the final design to close off the dry ingredients. The tolerance between the piston and mixing chamber is 0.005 inches. This tolerance is small enough to prevent leakage and yet allow the piston to move adequately within the chamber. A cap at the end of the mixing chamber acts as an additional barrier should leakage occur.

Cooking

Two main considerations were made in the purchase of a cooking unit. These considerations are as follows:

1. The unit must be adaptable to cook pancakes, waffles, and other flour-based foods so that the foods physically resemble thsoe food items.

2. The cooking surfaces of the unit must adapt so that foods of variable heights (such as muffins) can be cooked.

A cooking unit with removable plates and a variable height between the plates was purchased. The cooking unit is depicted in Figure 17.

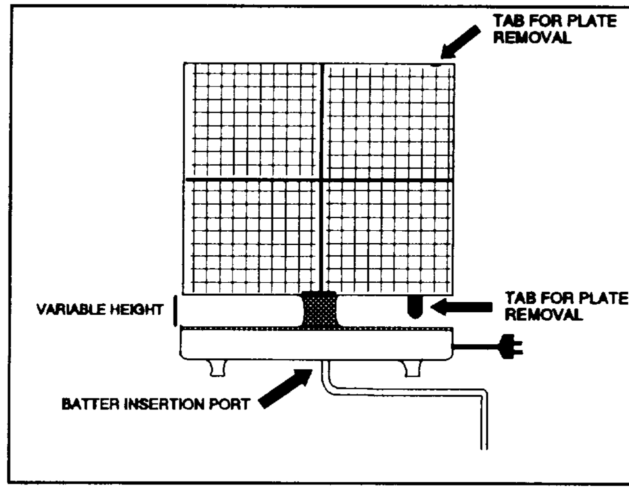

Fig. 17 The cooking unit

A port for batter extraction was connected at the end of the chamber (the same end as the ingredient insertion ports). A tube extends from the port, through the bottom center of the cooking unit, and into the space between the two plates. Because of time and cost limitations, it was decided that the tube would be removed upon injection of the batter. The complications associated with keeping the tube (and the batter within the tube) cool are eliminated by removing the tube from the cooking unit before cooking begins.

Conclusion

Final testing took place in all orientations. Each separate component of the device worked well as an independent unit. However, when all of the components were put together to assemble the final design, problems with leakage occurred. The ingredients leaked in two areas: (1) between the piston and mixing chamber walls and (2) at the connection for the dry ingredient container.

Dispensing wet ingredients into the mixing chamber did not present difficulties. The roll-off pinch valves acted to close off ingredients not being dispensed so that sequential ingredient insertion could take place. The check valves limited the flow of ingredients to one direction. Additionally, leakage did not occur at the entrance port to the chamber.

Favorable results were obtained from dry ingredient dispensing. However, the wet ingredients in the chamber leaked out around the connection of the dry ingredient container. This connection is sealed only by force applied at the opposing end of the container. Some modifications were made at the connection, and less leakage occurred.

As ingredients are inserted into the mixing chamber, the piston is intended to move back, keeping the system entirely air-proof. In the prototype, there was some difficulty in pushing back the piston. Also, there was some minor leakage around the piston.

The whisk mixed the ingredients into a smooth batter. It collapsed and extended during the proper stages of device operation.

The batter moved through the tube to the cooking unit with some difficulty. However, upon insertion of the batter into the unit, the batter spread evenly between the cooking plates.

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