The design and performance of an insect farm/chemical reactor for human food production[1]

R. KOK, K. LOMALIZA, and U. S. SHIVHARE

Agricultural Engineering, Macdonald College of McGill University, 21111 Lakeshore Rd., Ste Anne de Bellevue, Quebec H9X 1C0. *Received 6 July 1987, accepted 17 February 1988.*

Kok, R., Lomaliza, K. and Shivhare, U. S. 1988. **The design and performance of an insect farm/chemical reactor for human food production**. Can. Agric. Eng. 30: 307–317. This study demonstrated that it is technically feasible to mass produce insects for human consumption by industrial methods. A semi-continuous process was developed, based on the use of a single, batch-fed plug flow reactor and three basic unit operations. The material passed through the reactor in four streams of small, segregated batches with a phase lag of 2 d between them. In the process, the reactor performed four major functions, corresponding to the four streams: (1) feed conditioning (2) feed conversion, (3) dormant stage incubation (eggs, pupae) and (4) propagation (egg production). The process consists of two major "cycles", conversion and propagation, and the variables linking these are suitable for process control. The three-unit operations are sifting, air classification and solids mixing. The process was operated for a total of 364 d during two experiments with a test organism, *Tribolium confusum* (confused flour beetle). Several foods were prepared with the product pupae: bread, spaghetti sauce and hot dog wieners. These were consumed by volunteers and found to be palatable.

INTRODUCTION

The term "agriculture" refers to the set of symbiotic relationships existing between *Homo sapiens* and other species cooperating for the purpose of food, feed and fiber production; "farming" refers to the human activities oriented towards growing and harvesting the other species and their products (Kok 1983; Kok and Lomaliza 1986). Most of the symbionts are plants; among the animals, mammals and birds are most common although fishes and mollusks are also grown in significant quantities. Other taxonomic groups such as reptiles, amphibians, protists and insects are less likely to be found in agricultural symbiosis although several significant instances do exist for each of these. The honey bee and the silkworm have historically had great economic impact and the use of mass-reared insects for pest control is becoming common. Whereas in many cultures the use of insects for food is normal (Bodenheimer 1951; Taylor 1975), it is rare in technologically advanced societies. Insects offer, however, the means to convert cheap substrates directly to good-tasting, structured animal protein at high efficiency. Since more than a million species are available they offer considerable flexibility in process design and in matching feed supplies to product demand. Many conventional agricultural concerns can be disregarded in growing insects; whereas animal production is usualy a surface phenomenon, a large number of insect species can be grown volumetrically so that high productivity per unit facility volume and per unit capital cost can be achieved. The "animal rights" problem inherent in the industrial production of animal tissue is also not acute. Insects as farm animals can make a significant contribution to the nutritional requirements of their human partners and in this respect are especially interesting as potential components of autonomous, closed ecologies such as space stations and subaqueous and subterranean habitats. Farm technology to produce insects in large quantities is therefore under development. Insects are intermediate in size between protists and usual farm animals and various aspects of both production technologies (biotechnology and animal production) are applicable. In this case the "farm" can be treated as a biochemical process reactor and the conversion as a chemical reaction of which the feed and the insects are the reagents, the waste and the insect tissue the products.

The overall objective of the research program is to develop a process to produce insect tissue from low-grade cellulosic feeds. Because of the large number of unknowns and the lack of information, it was decided to first develop a functioning process with a well-known test organism. *Tribolium confusum* (confused flour beetle), on a feed which was readily available in standard form — unbleached white wheat flour mixed with dried brewer's yeast. The organism and feed chosen were therefore not of interest per se but were chosen for convenience only. Instead of *T. confusum* any one of several thousand similar species might be used. The intent is to create farm technology applicable to the production of a wide spectrum of species. The objectives for this study were therefore (1) to develop a process based on standard industrial unit operations, (2) to develop a reactor for feed conversion and organism propagation, (3) to ensure that, at least in principle, the reactor and process could be scaled up, (4) to operate the process to find major shortcomings and identify which variables would be most suitable and appropriate to manipulate for process control and (5) in a preliminary way, to investigate the manufacture of various foods from the product.

LITERATURE REVIEW

Although small, insects exceed in weight all other animal matter on the land areas of earth (Taylor 1975). Primitive humans, like present-day foraging omnivores such as monkeys, bears, badgers and skunks (Verts 1967; Long and Killingley 1983), undoubtedly obtained a considerable fraction of their protein, minerals and B vitamins entomophagously (Brothwell and Brothwell 1969). In more recent history several groups of insects e.g., locusts, crickets and grasshoppers, have specifically been accorded food status in codes of conducts such as

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the Bible and the Koran (e.g. Leviticus 11:20–23; Mark 1:6). Today, members from all major taxonomic divisions of insects are still intentionally consumed (Taylor 1975: Bodenheimer 1951) and are found as common trade items on many of the world's markets. Elorduy de Conconi (1982) has, for example, documented the significance of insects in the rural Mexican diet and Meyer-Rochow (1973) has described the reliance of central Australian tribes on the witchity grub for protein. Usually, the relationship between humans and food insects is predatory rather than agricultural and interaction consists of hunting, gathering activity instead of intentional rearing and harvesting. Food insects are also often gathered indirectly by means of intermediaries such as domesticated fowl which act as a collecting mechanism and nutrient concentrator at the cost of lowered yield. True agricultural activity to produce insects for food is less common although remarkably similar instances of this have been reported from New Guinea, South America and Africa. Taylor (1975) has described how the Papuans will fell a sago palm, cut its bark to let in adult beetles and return 6 weeks later to harvest the grubs. Chagnon (1968) has documented a very similar approach to "insect domestication" on the part of the Yanomamo and Oliveira et al. (1976) have indicated that analogous practices are followed in Angola. When insects are reared for purposes other than consumption, as by-products they may still constitute a significant food source. Hoffman (1947) has described how in China silkworm pupae were commonly eaten by workers in the reeling operation and the human consumption of discarded bee brood has been suggested by a number of authors (e.g., Caron 1978; Taylor 1975; Ozimek et al. 1985) since many tonnes of this material are destroyed annually due to wintering problems.

Most of the development in insect mass production technology has been in the Sterile Insect Technique field. Clarke (1984) has described a rearing facility to produce a billion fruit flies (about 7 tonnes) a week in Egypt. The total project cost was US$ 50 million to maintain that release rate for 1 year so that the unit cost was US$ 143 per kg of fruit fly. Taylor (1975) has suggested that the usual apiary operating scheme might be modified to favor the production of bees rather than honey so that apiculture would become protein rather than saccharide oriented. Although apiary technology is well known and widely practiced at the craft level (i.e., small production units with large human labor inputs), its industrialization has not yet been implemented. Many authors have proposed mechanized schemes to use animal wastes as substrates to grow insects (e.g., Koo et al. 1980; Morgan and Eby 1975) but always to produce animal feed rather than food for humans. Stanley (1951, 1953) constructed an apparatus he called the Autotrephon which functioned automatically and maintained a colony of *T. confusum* for scientific study. Although the various schemes above are all concerned with "mass production", their costs and/or capacities are several orders of magnitude different from what is envisaged as being required to significantly impact the global food situation. In a world of 10 billion humans each requiring 40 g protein per day (dry weight) it might be desirable to stabilize protein prices by supplying 10% of total demand with insects. This would create a demand of 200 million kg/d of live insect tissue (protein 40% of wet weight, 50% of tissue weight utilizable). A reasonably sized plant might capture 0.5% of this market and would thus need to produce 1000 tonnes/d and a world-scale plant might be 10 times as large. Real production cost (i.e., without subsidization) would need to be about US$1.00/kg utilizable dry protein, corresponding to US$0.20/kg liveweight. Similarly, a unit to supply 100% of the protein requirement for a space colony of 10,000 would need to produce 2,000 kg/d liveweight. No design methods for processes and reactors of this scale are available although valuable insights about the entomological aspects of industrial production have been published by a number of authors (e.g., Leppla and Ashley 1978; Bell et al. 1981). A major challenge will be to find or breed an organism that optimally meets all requirements (Kok 1983).

Tribolium confusum is a Coleopteron of the family Tenebrionidae and is found wherever cereal products are stored. Its life cycle consists of four stages: egg, larva, pupae and adult. The egg major and minor diameters are approximately 0.65 and 0.35 mm respectively and the eggs are covered with a sticky fluid that accumulates flour and dust particles (Cotton and Wilbur 1974). A newly hatched larva has a length of 1.2 mm and a width across the head capsule of 0.2 mm. The larvae are yellowish-white and undergo from 5 to 12 molts. They crawl through their feed and can be submerged for their entire development period; they are 5.0 by 0.8 mm when ready to pupate (Roth and Howland 1941). Pupation occurs on the surface of the medium and the pupa is white until the middle of the pupation period when it gradually turns pale yellow and finally brown. The claws and the tips of the mandibles turn dark brown just before eclosion. Immediately after emergence the adult is soft, inactive and light brown but in 1 to 2 d the exoskeleton hardens and the beetle becomes reddish-brown. The adults are about 3.5 mm long and 1.0 mm wide in the thoracic region and have odoriferous glands that secrete a pungent liquid containing quinones which interact with flour and can give it a pink appearance (Roth and Howland 1941). These quinones are also suspected of being tumorigenic (Gorham 1979). The development and life cycle of *T. confusum* are very strongly influenced by the temperature, relative humidity and nutrition available. Optimal environmental conditions are 32°C, a water activity of 0.7 (Howe 1960) and a coarsely ground feed containing adequate nitrogen e.g., supplied as wheat germ or yeast (Roth and Howland 1941). Under these optimal circumstances the development from egg to adult requires approximately 30 d. Adults will live for several months and females will deposit 400 or more eggs at a rate of 6 – 12 daily. The adults will spend some of their time on the feed surface but most of it in burrows. Both adults and larvae are cannibalistic and will consume eggs and pupae (Cotton and Wilbur 1974). *Tribolium confusum* is used very widely for scientific studies and has been extensively described in the literature (e.g., Sokoloff 1972, 1974, 1977). Mills and Pepper (1939) demonstrated that its ingestion by humans in quantity caused no discernible harm, Roth (1943) pointed out that both the larvae and pupae are odorless although adult beetles have an unpleasant taste and Sokoloff (1974) described how the immature stages "when fried in oil and lightly salted... are somewhat shrimp-like and perfectly acceptable" as human food.

MATERIALS AND METHODS

During preliminary studies non-flying Coleoptera were found to be the most suitable and a number of cellulose-feeding target species e.g., *Stegobium paniceum*, were identified. *Tribolium confusum*, although a starch consumer, is also a stored-products pest and is quite similar to *S. paniceum* in size, habits and environmental requirements. Moreover, it is very well known, convenient to work with and relatively simple to confine by restricting its food supply. This was significant because possible mass

escape of a cellulose feeder during process development gave cause for concern. The various idiosyncrasies of *T. confusum* such as its partial cannibalism, quinone secretion and surface area requirement for pupation and adult behavior did not, in this case, impose restrictions on the reactor or process design but under different circumstances might prove to be limiting. The reactor was of the batch-fed plug-flow type, containing a large number of small batches of material, regularly out of phase with each other. These batches were arranged as shallow beds in trays and thus were kept totally segregated. Reactor operation was therefore easily adjustable and all material was readily identifiable while a large surface area per unit mass was available for heat and mass transfer. The reactor performed four functions in the process: (1) feed conditioning, (2) feed conversion, (3) dormant stage incubation (eggs and pupae) and (4) propagation (egg production). Due to the nature of the reactor, the process was operated semicontinuously (but could operate continuously with a different reactor) with a phase lag of 2 d between batches but some actions taking place each day to distribute the work load. The three unit operations used were solids mixing, sifting and air classification and the process consisted of two major cycles, conversion and propagation, with the variables linking these being suitable for process control. The major variables available for manipulation were therefore: reactor environmental conditions, division of organism total residence time into stages, mass ratio of eggs to feed, mass ratio of egg-producing adults to feed, adult residence time and degree of feed recycle. During preliminary work values for these were established which allowed the process to operate in a quasi-stable but sustainable manner and two experimental runs, each lasting several months, were completed.

Fresh feed was made up of 95% (wt) unbleached white wheat flour (Buffalo; Ogilvy) and 5% dried brewer's yeast which had been ground to pass a No. 80 sieve. *Tribolium confusum* was isolated from a naturally occurring population and, when necessary, organisms were killed in an autoclave. Solids mixing was done manually in batches. Fresh feed was prepared 10 kg at a time and a uniform color was usually obtained after 20 min. Fresh and recycle feeds were mixed in smaller batches as required to fill the trays. Eggs were gently stirred into the feed on the trays whereas larvae, pupae and adults were simply sprinkled on the surface. Sifting was done with stacked sieves (Canadian Standard Nos. 30, 60, 70, pan; Tyler) held in a cage mounted on a modified gyrotory shaker (Model G2; New Brunswick) rotating at 450 rpm. To separate the contents of a tray, the material on it was dumped via a hopper onto the top sieve and shaken until the fractions were segregated as determined by visual inspection. After sifting the fractions were transferred to preweighted containers and weighed. Larvae and pupae retained on the No. 30 sieve were further separated by air classification from low density wastes largely consisting of pupal casings and larval molt skins. Compressed air was blown through the mixture so that the light fraction was lifted up and this was aspirated with a vacuum cleaner. The reactor was a modified plant growth incubator (Model EY8L; Controlled Environments) in which the temperature and relative humidity were controllable. Two racks were built into the incubator so that 144 steel trays (43 × 28 × 2 cm) could be placed inside. An air circulation circuit was also installed to achieve homogeneous conditions throughout. Air was therefore used for both heat and the mass transfer of gaseous reactants and products. Neither the fresh air flow to the reactor nor the internal circulating air flow were controlled. The reactor is illustrated in Fig. 1. All

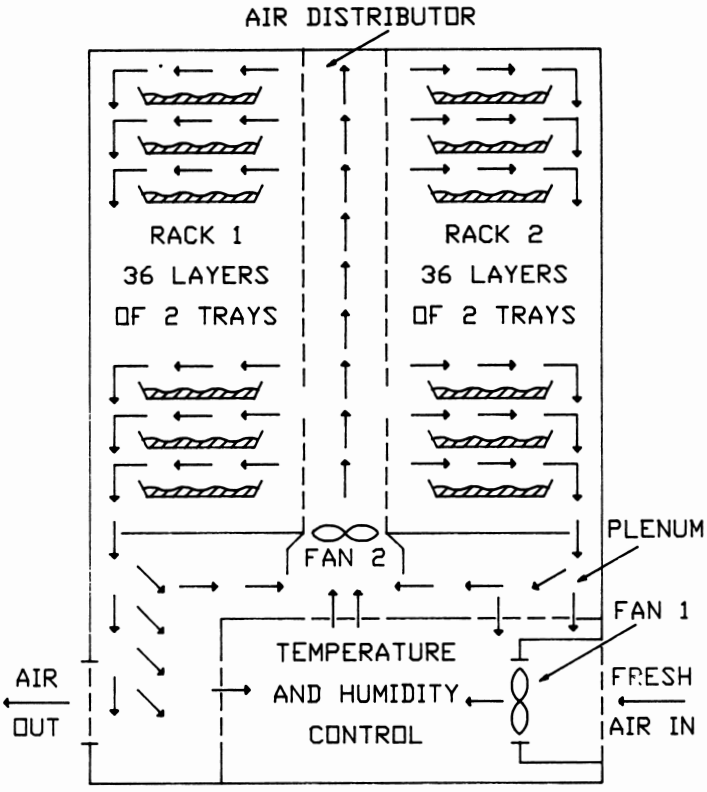

Figure 1. The reactor.

trays were filled with 400 g of feed before being placed in the reactor for conditioning. The reactor environment was controlled at 32°C and 85% relative humidity for both experiments.

The flowchart of the process used for exp. 1 is shown in Fig. 2 and operations are indicatd to have occurred on odd or even days. For exp. 1 all operations were done in groups of two trays and each group was treated as a unit throughout the process. The four reactor functions are labelled as "feed conditioning" (one block) and "incubation" (three blocks) and the number of trays present in the reactor at any time, associated with a given function, is indicated in each block. The feed trays for the eggs/larvae and for the pupae were conditioned for 10 d whereas those for the adults were conditioned for 2 d. Conditioning consisted of the trays simply being resident in the reactor to allow the feed to absorb moisture. In exp. 1 egg dormancy, larval growth and pupation were combined in a single incubation and this, together with the associated operations, is referred to as Cycle 1. The natural distribution of organism development times was compensated for by a separate pupal incubation which was long enough so that practically all organisms were reproductive adults at the end. Cycle 2 consisted of adult incubation and egg collection. Every time eggs were collected 32 trays (16 groups of 2) were sifted, the two oldest trays discarded and two new adult trays added from the pupal incubation. Thus, adults were killed 32 d after entering Cycle 2 and having had their eggs collected 16 times. The total organism residence time was 58 d, divided into three incubations. The two major control variables linking Cycles 1 and 2 were set at: egg inoculation 1 g/tray (mass ratio 0.0025 eggs:feed) and initial pupal density 5 g/tray (mass ratio 0.0125 pupae:feed). For the egg/larval feed trays 12% fresh feed and 88% recycle feed no. 1 was used, for the pupal trays 100% fresh feed was used and for the adult trays 17% fresh feed and 83% recycle feed no. 2. For process startup the conditioning of two egg/

larval trays (Group 1) was begun on Day 1 and on Day 11 these were inoculated with eggs from a seed colony. After a total of 32 d of operation Group 1 was moved to pupal incubation and on Day 39 the first eggs were collected from them. These were used to partially inoculate Group 20 but since there was not enough, they were combined with eggs from the seed colony. It was not until Day 55 that Cycle 2 was sufficiently stabilized and produced enough eggs to fully meet the inoculation requirement (2 g) so that Group 23 was the first to be completely "reactor native". The adults producing these eggs were, however, still of seed colony origin and only by Day 111 (just after Group 22 had been discarded from Cycle 2) was full reactor nativity established. Before process steady state can be assumed, a common requirement is that a system operate for three residence times. According to this criterion, a total unsteady state period of about 185 d would need to be supposed and, ideally, only data collected after that should be used for process evaluation. In this case that approach was not possible for practical reasons; Cycle 1 data were collected until Day 192 (separation of Group 81 larvae) but Cycle 2 was operated only until Day 171.

RESULTS — EXPERIMENT 1

Data for Groups 23 to 81 (59 groups, 118 trays) were used for the Cycle 1 analysis. For each group the two-tray averages were calculated for: recycle feed no. 1, wastes no. 1, light and heavy fractions from the air classification (the heavy fraction being the product organisms) and combined wastes (wastes no. 1 and light fraction). These recycle no. 1, combined wastes and product values for the groups are shown in Fig. 3. This gives an impression of Cycle 1 stability during process quasi steady state. The mean values for recycle no. 1, wastes no. 1, light waste and product were respectively (means of 59 group values, standard deviations shown in brackets): 340(14.6), 3.5(1.4), 0.26(0.16) and 20(5.3) g/tray. Since originally 400 g feed and 1 g eggs had been added per tray, on the average 37 g/tray disappeared over a 21-d period during Cycle 1 and a consumption of 60 g feed resulted in a gain of 19 g organism so that the gross yield ratio was 0.32.

For the analysis of Cycle 2, only the data obtained after Day 111 were used and for every group-day combination, for each of two trays, weight values for four variables were available: adults, eggs, wastes no. 2 and recycle feed no. 2. First, two-tray group averages were calculated for each combination, resulting in the data block shown in Fig. 4. The results were then interpreted in three ways: horizontally, vertically and diagonally. Horizontal analysis is useful to study Cycle 2 stability on a day-to-day basis. For each of the 30 sifting days (Day 113 –171) average horizontal values (of 16 groups) were calculated for each of the four variables and these are shown in Fig. 5. The means of these horizontal averages are reported in Table I. Tray-to-tray variability can be examined with vertical analysis. Complete vertical data (i.e. for 16 siftings) were available for 15 groups (Groups 38 – 52) and average values for the four variables were calculated for these; the means of these vertical averages are shown in Table I. Diagonal analysis is the most relevant to study process performance since it reveals the lifetime behavior of the groups during Cycle 2 operation. For each of the 16 siftings any group underwent, average diagonal values (of 30 groups) were calculated for the four variables. These are plotted in Fig. 6. As shown in Table I, the means of the diagonal averages were the same as for the horizontal analysis but the standard deviations were different. On the average (from horizontal and diagonal analysis) 3.6 g of adults produced 0.26 g eggs/d and 0.48 g wastes no. 2/day while using 2.7 g feed/d. Daily mass disappearance during Cycle 2 was 2.0 g/tray.

DISCUSSION — EXPERIMENT 1

The mass disappearance observed during Cycle 1 was presumably due to metabolism of feed to carbon dioxide and water and the convection of these. The variations in Cycle 1 results (Fig. 3) are thought to have been caused by a number of factors which were difficult to control during the 192 d of the experiment: (1) although the same type flour was bought from the same supplier, differences in flour behavior during sifting were observed (e.g. flour from different purchases moved through the sieves at different speeds) and (2) reactor relative humidity was not always stable and the humidity control system suffered several breakdowns during the experiment. As a result, the separation of wastes no. 1 from recycle no. 1 and flour adherence to the eggs may have been affected. Although 1 g of eggs was consistently added per tray, the viable weight of eggs added may therefore have varied, causing fluctuations in the product yield. This is also supported by the fact that recycle no. 1 and product were strongly and negatively correlated (coefficient −0.96, significant at 0.01 level). Combined waste was not correlated with either recycle no. 1 or product.

The day-to-day variability of Cycle 2 operation, evidenced by horizontal analysis (Fig. 5, Table I), was due to the factors described above which also caused Cycle 1 variations, as well as inaccuracies in the weighing procedure. A number of negative values were obtained for wastes no. 2 and eggs since the tare weights of the containers were rather large compared to the quantities of the materials. From vertical analysis it appeared that tray-to-tray variability in producing eggs was slight (Table I, S.D./mean = 0.05). From diagonal analysis it may be concluded that during the 32-d residence of adults their net weight decreased slightly, together with their egg and waste production. These three variables were significantly correlated (coefficients 0.64, 0.97 and 0.67, respectively, all significant at the 0.01 level).

The addition of 1 g of eggs per tray containing 400 g feed resulted in a recycle no. 1 of 340 g, indicating that a higher inoculation level and therefore a greater productivity per tray might be feasible. As is evident from Fig. 6, adults were still producing eggs when discarded after 16 siftings. Pupae were therefore wasted in creating new adults since the old ones might have been kept longer. Also, it may be possible to operate Cycle 2 with an initial loading higher than the 5 g pupae/tray used, so that egg production per tray could be increased. On the average, 17 g eggs were collected per sifting day but only 2 g were used for inoculation and the rest discarded. Adequate eggs might thus be produced with fewer adult trays. Since egg collection was the most time-consuming operation of the process, this would be quite beneficial. Experiment 2 was designed to take advantage of several of the above possibilities.

METHODS — EXPERIMENT 2

The process flowchart for exp. 2 is shown in Fig. 7. The group size for operations was 1 tray. The process used was similar to that used for exp. 1 but the following changes were incorporated: (1) the period of egg dormancy and larval growth was divided into two stages so that larvae were put onto fresh feed just before pupation, (b) adults were allowed to emerge and mature during an 11-d incubation to become fully reproductive

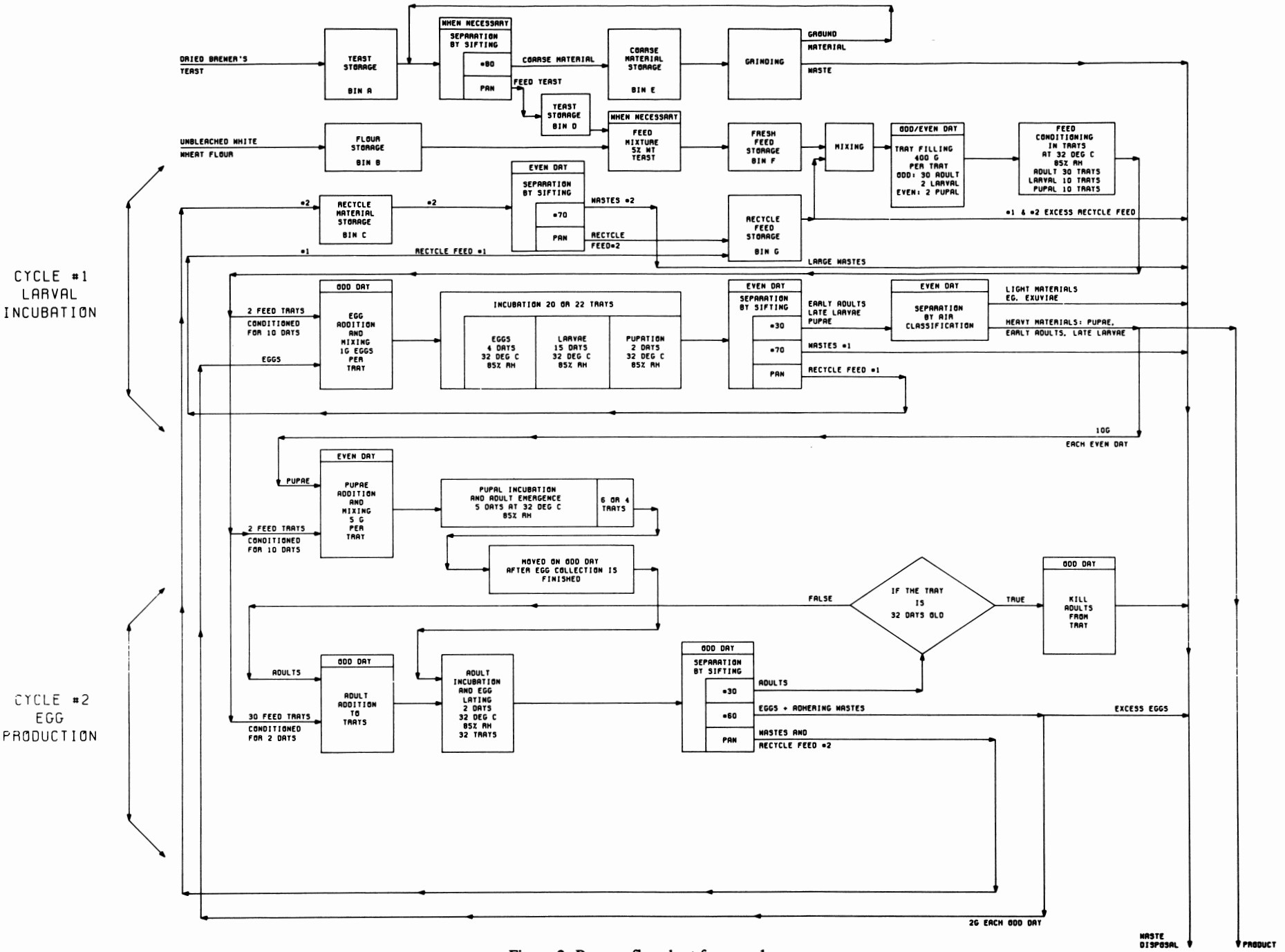

Figure 2. Process flowchart for exp. 1.

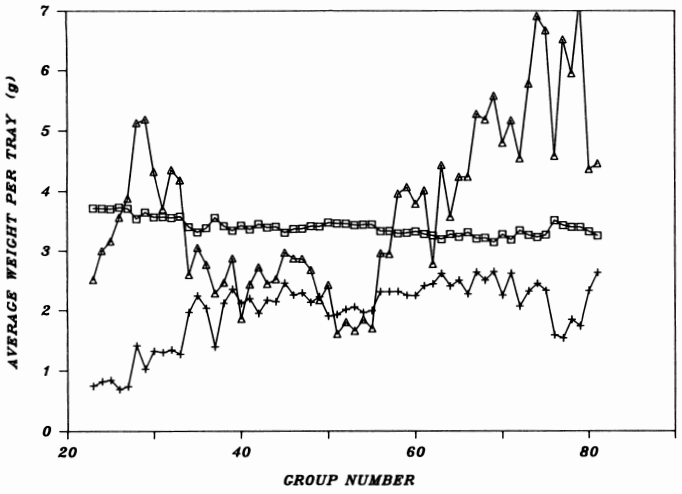

Figure 3. Experiment 1, Cycle 1 results. □, 0.01 × recycle no. 1; +, 0.1 × product; Δ, combined wastes.

and then were separated from their feed by sifting and air classification before being moved to Cycle 2; and (c) the eggs were cleaned before being used for inoculation. Extra feed preparation, feed conditioning, sifting and air classification steps were required to implement these adjustments and several more recycle and waste streams were created. All feed for the experiment was prepared from the same batch of flour and the weighing procedure was modified to allow for more accurate measurements. Total organism residence time was 100 d, divided into four incubations of 19, 6, 11 and 64 d respectively. Egg inoculation was at 2 g/tray (mass ratio 0.005 eggs/feed) but this is not directly comparable to the 1 g/tray used for exp. 1 since in this case the eggs underwent an extra cleaning. During preliminary work higher inoculation levels were tried but larvae failed to pupate. It was not clear if that was due to a shortage of feed or a chemical inhibition mechanism. At the 2 g/tray inoculation level the larvae would only pupate if they were placed on fresh feed and this is why the extra larval incubation stage was used in Cycle 1. As in exp. 1, pupae were added at 5 g/tray. Adults were kept in Cycle 2 for 64 d and were sifted 32 times before being discarded (32 d and 16 times for exp. 1). Every time eggs were collected, 32 trays were sifted, the oldest one discarded and a new one added. Although it was wasteful of reactor volume and labor to keep 32 adult trays, it ensured an adequate supply of eggs. For process startup the conditioning of an egg tray (Group 1) was begun on Day 1 and on Day 11 it was inoculated with seed colony eggs which had been collected and cleaned in the same way as shown in the flowchart. On Day 30, Group 1 underwent its first separation and the organisms were added to a fresh feed tray (whose conditioning had begun on Day 20) and moved to larval incubation. On Day 36 it was separated again and 5 g of pupae was moved to pupal incubation. On Day 47 these were again separated and moved to an adult tray in Cycle 2. Group 1 eggs were collected for the first time on Day 49 and Group 1 was discarded on Day 111, 110 d after being created. It was not until Day 61

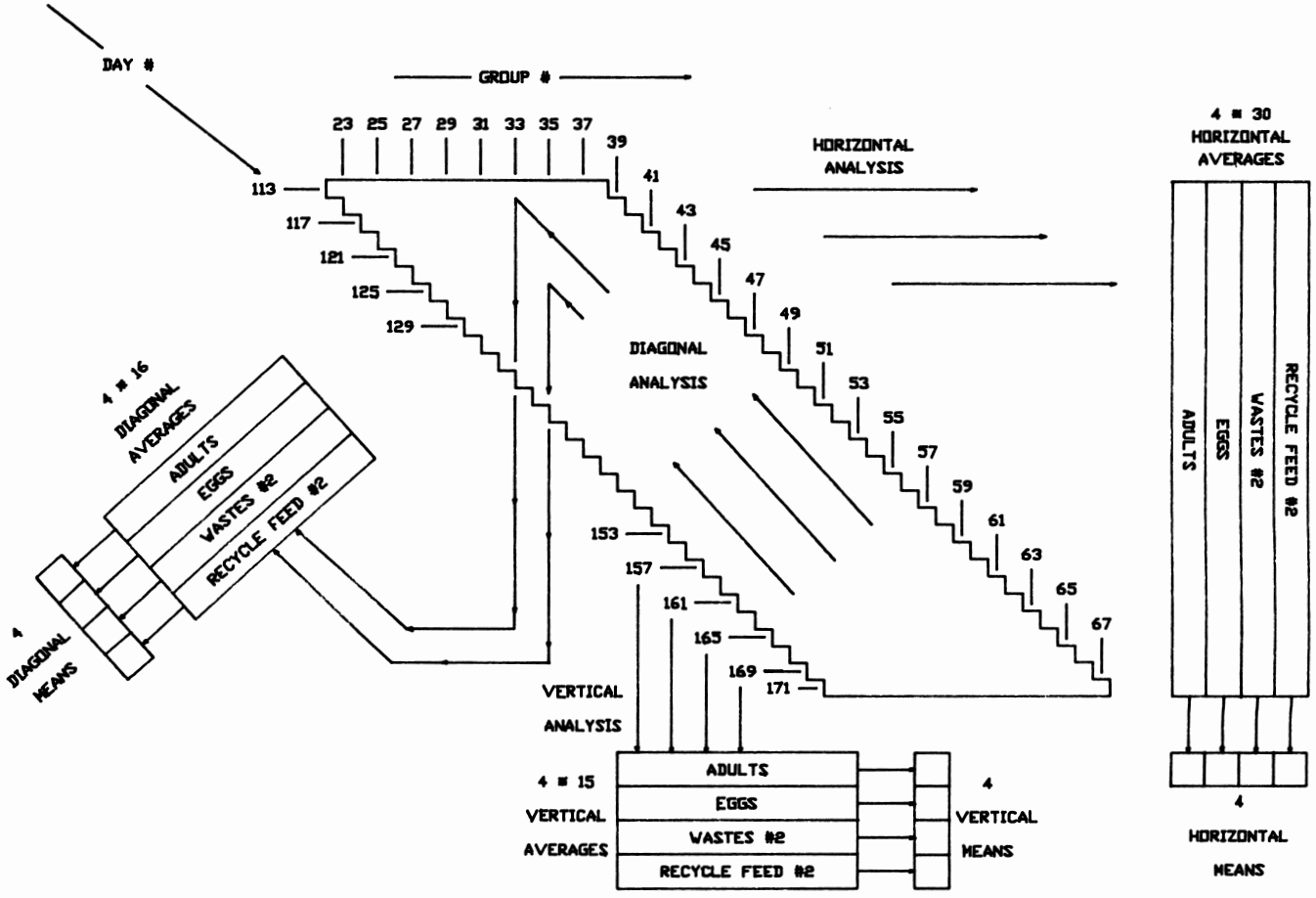

Figure 4. Data block for exp. 1, Cycle 2 analysis.

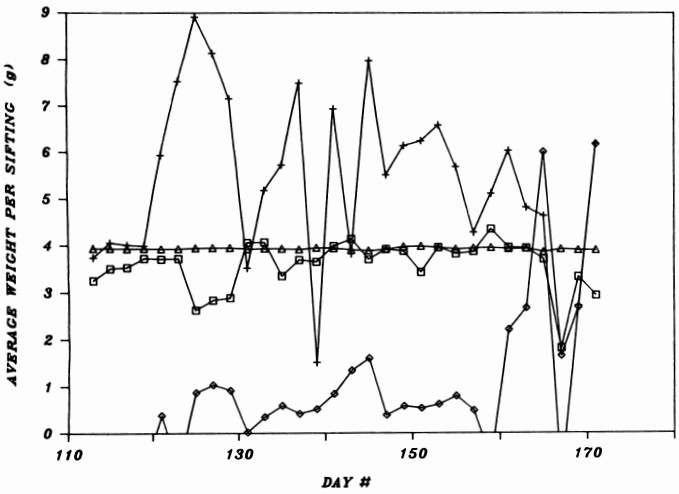

Figure 5. Experiment 1, Cycle 2 horizontal analysis results. □, adults; +, 10.0×eggs; ◇, wastes no. 2; Δ, 0.01×recycle no. 2.

that Cycle 2 produced 2 g of clean eggs so that Group 31 was the first to be reactor native. Group 30 was, however, not discarded until Day 169 and the last egg collection took place on Day 171 so that during exp. 2 the population was fully native for only 2 d. Since organisms were resident for 100 d, an unsteady state period of 300 d would need to be supposed according to classical criteria. It was physically not possible to implement this and data were collected only until Day 172.

Table I. Overall results of exp. 1, Cycle 2 analysis

	Direction of analysis		
	Horizontal	Vertical	Diagonal
No. of averages used to calculate mean and SD	30	15	16
Weights (g per tray per sifting)			
Adults			
Mean	3.59	3.63	3.59
SD	0.53	0.31	0.38
Eggs			
Mean	0.53	0.56	0.53
SD	0.21	0.03	0.07
Wastes no. 2			
Mean	0.96	0.56	0.96
SD	1.70	0.27	1.02
Recycle no. 2			
Mean	394.53	395.33	394.53
SD	2.37	0.25	1.61

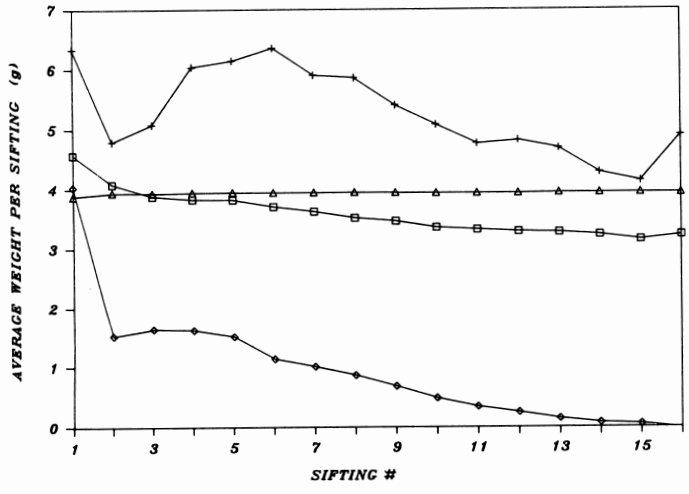

Figure 6. Experiment 1, Cycle 2 diagonal analysis results. □, adults; +, 10.0×eggs; ◇, wastes no. 2; Δ, 0.01×recycle no. 2.

RESULTS — EXPERIMENT 2

Complete Cycle 1 data for reactor native organisms were available only for Groups 31 – 63 (33 groups; Group 63 was put onto an adult tray for the first time on Day 171) and for these the statistics of the various mass streams are reported in Table II. On the average, 80 g disappeared per group during the 25 d required to pass from egg to pupa and a consumption of 184 g feed resulted in a gain of 37 g organism for a gross yield ratio of 0.20.

For Cycle 2 analysis data obtained on Days 111 through 171 were included. One-half of these were for non-native organisms since the last sifting of Group 1 and the first sifting of Group 32 both took place on Day 111. Due to the longer retention of reproductive adults, the diagonal thickness of the data block (Fig. 4) was 32 rows rather than 16 as in exp. 1 and vertical analysis could not be performed because there were no completed sifting data included for any given group. The data block had a width of 62 groups and a depth of 31 sifting days. For each of the 31 sifting days average horizontal values (of 32 groups) were calculated for: adults, eggs, wastes no. 4 and recycle no. 4. These are plotted in Fig. 8. For each of the 32 siftings any group underwent, average diagonal values (of 31 groups) were calculated for these same four variables and they are shown in Fig. 9. The means and standard deviations are reported in Table III. On the average, 2.7 g adults/tray produced 0.21 g eggs/d and 7.2 g wastes no. 4/d while using 10.2 g feed/d. Daily mass disappearance was 2.8 g/tray. Per sifting day an average of 13.3 g eggs was collected and after cleaning 7.7 g remained.

DISCUSSION

During exp. 2, the separation of wastes from recycle feeds was problematic and was caused by variable performance of the humidity control system. This is reflected in the large values of the coefficient of variation for the waste streams (wastes no. 1, 0.42; no. 2, 0.65; no. 3, 0.66; no. 4, 0.67). This problem also lowered the gross organism yield to 0.20 from 0.32 obtained in exp. 1 because feed was thrown away with the waste. The net yields (organisms produced per mass disappeared) for the two experiments were 0.51 and 0.47, respectively, but a much higher productivity was attained during exp. 2 (37 vs. 19 g/tray). The ratio of these productivities was 1.9:1 although the egg inoculation ratio had been 3.45:1 if the extra egg cleaning step is taken into account. Daily organism productivities were 1.5 and 0.90 g/tray.day so that the ratio of these was 1.7. Egg cleaning may have improved Cycle 1 stability since the coefficient of variation of the product stream weights was reduced from 0.27 to 0.12 (exp. 1 vs. exp. 2).

On a day-to-day basis (horizontal analysis) egg and adult weights were more stable during exp. 2 than 1 (coefficients of variation: 1, 0.40, 0.15; 2, 0.23, 0.06, respectively). This may have been due to the improved weighing method. The mean waste stream value of 14.35 g/tray.sifting from exp. 2 was radically different from the 0.96 obtained for exp. 1. As also observed in exp. 1, over the residence time of the adults (diagonal analysis) waste production gradually decreased and the adult and egg weights were rather stable. In this respect the

Table II. Experiment 2, Cycle 1 results†

Stage or mass flow (g/group)	Avg.	SD	Totals: Input, output	Totals: Mass loss	Waste
Egg incubation					
Input					
Feed	400				
Eggs	2.00				
Total	402	.....	402		
Output from sifting					
No. 30 — larvae	37.74	4.16			
No. 70 — wastes no. 1	17.30	7.32	.....		17.30
Pan — recycle no. 1	289.44	14.89			
Total	344.48	.....	344.48		
Mass loss — egg incubation			57.52	... 57.52	
Larval incubation					
Input					
Feed	400				
Larvae	37.74	4.16			
Total	437.74	.....	437.74		
Output from sifting					
No. 30 — pupae & waste	39.80	4.84			
No. 70 — wastes No. 2	49.14	31.87	.....		49.14
Pan — recycle no. 2	326.14	31.96			
Total	415.08	.....	415.08		
Mass loss — larval incubation			22.66	... 22.66	
Output from air classification					
Product pupae	39.50	4.84			
Light waste	0.30	0.08	.....		0.30
Total mass loss during pupae production				80.18	
Total waste for pupae production					66.74
Pupal incubation					
Input					
Feed	400				
Pupae	5.0				
Total	405	.....	405		
Output from sifting					
No. 30 — adults & waste	4.22	0.28			
No. 70 — wastes #3	68.43	44.84	.....		68.43
Pan — recycle #3	330.59	44.52			
Total	403.24	.....	403.24		
Mass loss — pupal incubation			1.76		
Output from air classification					
Product adults	4.01	0.29			
Light waste	0.21	0.04	.....		0.21
Total waste during pupal incubation					68.64

†Values are statistics of 33 measurements: Groups 31 – 63.

results from the two experiments are, however, not directly comparable since in exp. 2 the adults were older when added to Cycle 2. Mean adult weight was lower during 2 than 1 (2.7 vs. 3.6 g/tray) but mean daily egg yields were the same (0.078 g egg/g adult.day before cleaning).

In comparing exp. 2 to exp. 1, the various adjustments in the process had as major effects: (1) a higher Cycle 1 production per tray was attained while the net yield remained the same, (2) the process was more efficient because a smaller fraction of the pupae was used for adult replacement and (3) egg cleaning improved Cycle 1 stability. The process was, however, considerably more complex, more reactor space was used for non-productive activities such as feed conditioning and pupal incubation, the conversion of egg to pupae took 4 d longer, there were extra handling steps and separations to perform and more storage space was required. An egg inoculation level between those used for exps. 1 and 2 might eliminate the need for the larval incubation. After 64 d, egg production by adults had not decreased substantially and process efficiency might be increased further by keeping adults longer. No significant death toll was observed in the adult population during their residence so that adult loading per tray could probably be increased and the number of adult trays decreased. This would reduce the work associated with egg collection. On each sifting day an

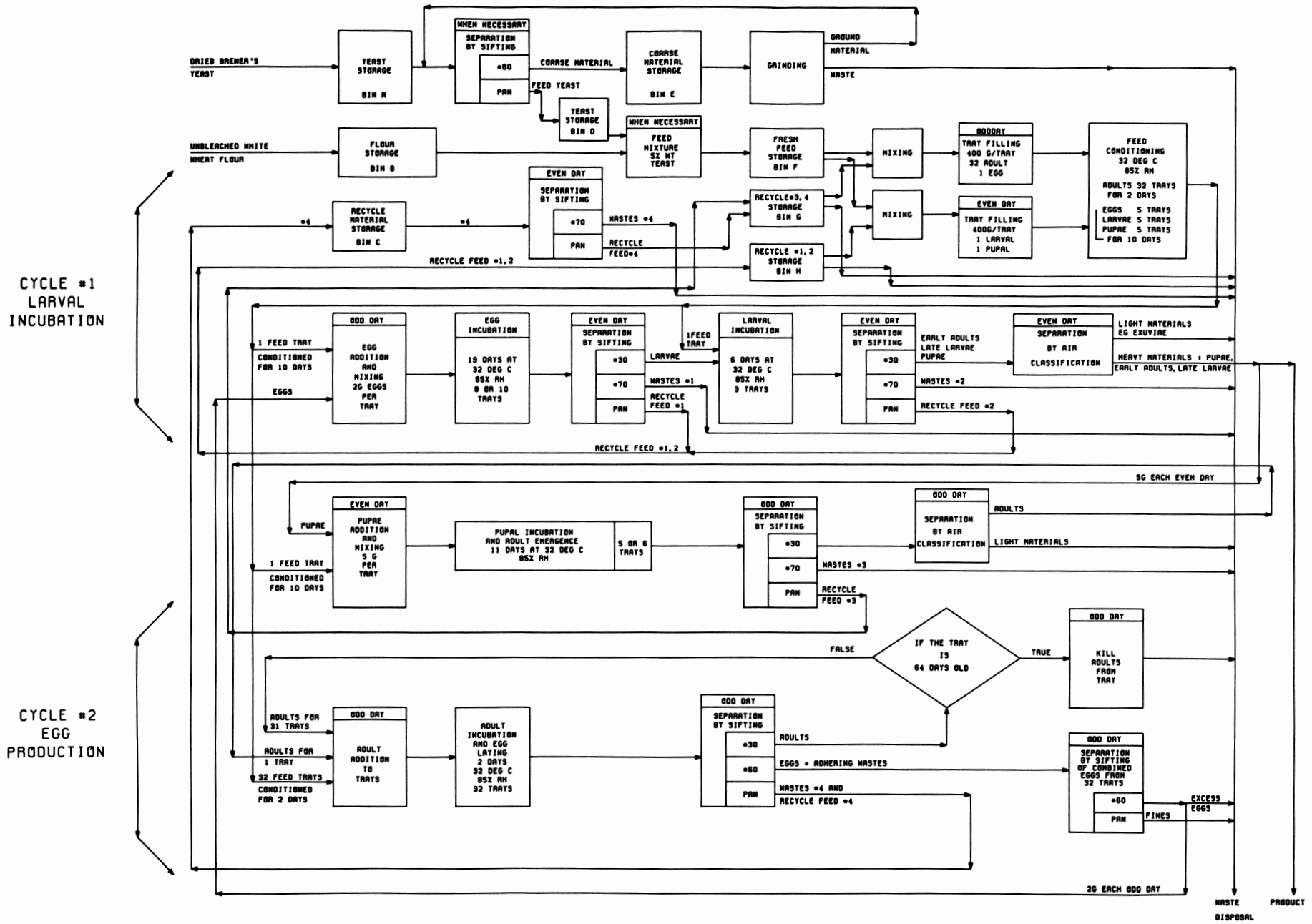

Figure 7. Process flowchart for exp. 2.

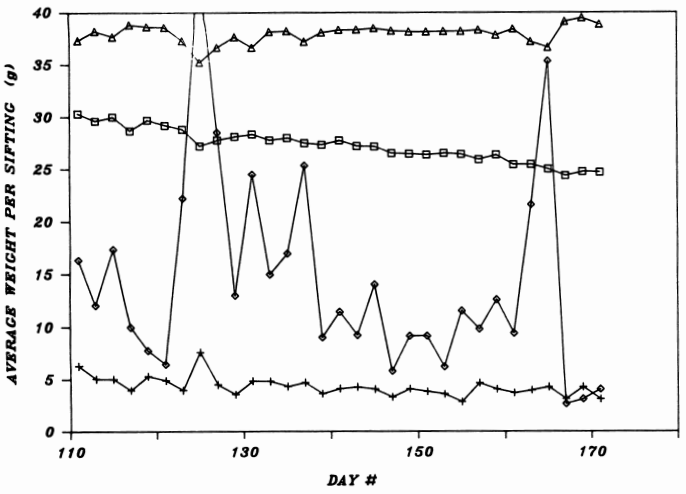

Figure 8. Experiment 2, Cycle 2 horizontal analysis results. □, 10.0 × adults; +, 10.0 × eggs; ◇, wastes no. 4; Δ, 0.10 × recycle no. 4.

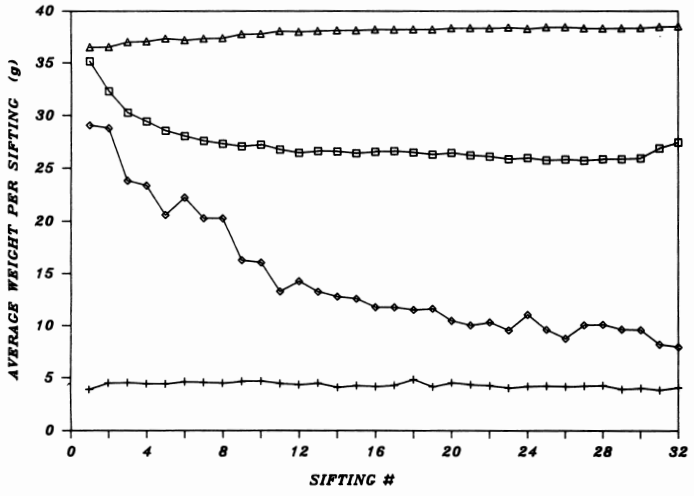

Figure 9. Experiment 2, Cycle 2 diagonal analysis results. □, 10.0 × adults; +, 10.0 × eggs; ◇, wastes no. 4; Δ, 0.10 × recycle, no. 4.

Table III. Overall results of exp. 2, Cycle 2 analysis

	Direction of analysis	
	Horizontal	Diagonal
No. of averages used to calculate mean and SD	31	32
Weights (g per tray per sifting)		
Adults		
Mean	2.72	2.72
SD	0.16	0.20
Eggs		
Mean	0.43	0.43
SD	0.10	0.02
Wastes no. 4		
Mean	14.35	14.35
SD	9.56	5.98
Recycle no. 4		
Mean	379.55	379.55
SD	8.58	5.79

average of 7.7 g clean eggs was collected but only 2 g were used for inoculation. The total amount of adults kept in Cycle 2 could therefore be halved while maintaining an adequate safety factor. Much of the process variability was caused by malfunctioning of the humidity control system; adequate control of relative humidity in the reactor is essential if sifting is to be used for the separations.

Over the course of the two experiments a total of 4 kg of product was collected. Some of this was frozen and some was freeze-dried. The frozen material was incorporated into bread (5%) as a protein fortification agent and in spaghetti sauce (10%) as a meat replacement. It was also used as the main ingredient in a hot dog wiener recipe. The bread, sauce and wieners were informally submitted to taste panels for evaluation. None of the panelists detected any objectionable taste or odor and all products were rated as very acceptable.

CONCLUSIONS

The reactor based on batches arranged in shallow beds and confined in trays was successfully used for organism conversion and propagation as well as dormant stage incubation and feed conditioning. The approach allowed complete segregation between batches to be maintained so that the organism age distribution remained narrow throughout the process. Because of this reactor characteristic the process was very straightforward. The process was based on several standard unit operations and could, in principle, be scaled up to industrial size. As long as a sufficient fraction of the pupae is used to produce new adults, the process is sustainable. Process efficiency can be affected by manipulating the variables connecting the two cycles (eggs/feed and adults/feed mass ratios), as well as variables internal to the cycles (safety factor in egg production, life cycle division) and process and reactor operating variables (e.g., temperature, relative humidity). The degree of feed recycle will also strongly influence overall efficiency. Although the particular organism used in this case to test the process and reactor arrangement is not interesting as a human food source, its pupae were consumed in quantity without noticeable ill effect. The product is palatable when cooked and several foods were prepared in demonstration quantities.

The technical feasibility of producing insects for human consumption by means of an industrial approach has been demonstrated. Mass balance, kinetic and thermodynamic aspects of the process are being studied and will be reported upon in a subsequent publication. Future work will include: (1) development of a deep-bed reactor; (2) modification of the process to accommodate semicontinuous, deep-bed operation; (3) selection of a fast-growing, cellulose-consuming, edible insect whose development can be tightly synchronized; (4) manufacture of a cheap, granular, cellulose-based feed; (5) exploration of the potential to feed the process waste to other species e.g., fish; (6) nutritional analysis of the product; and (7) economic analysis of the process.

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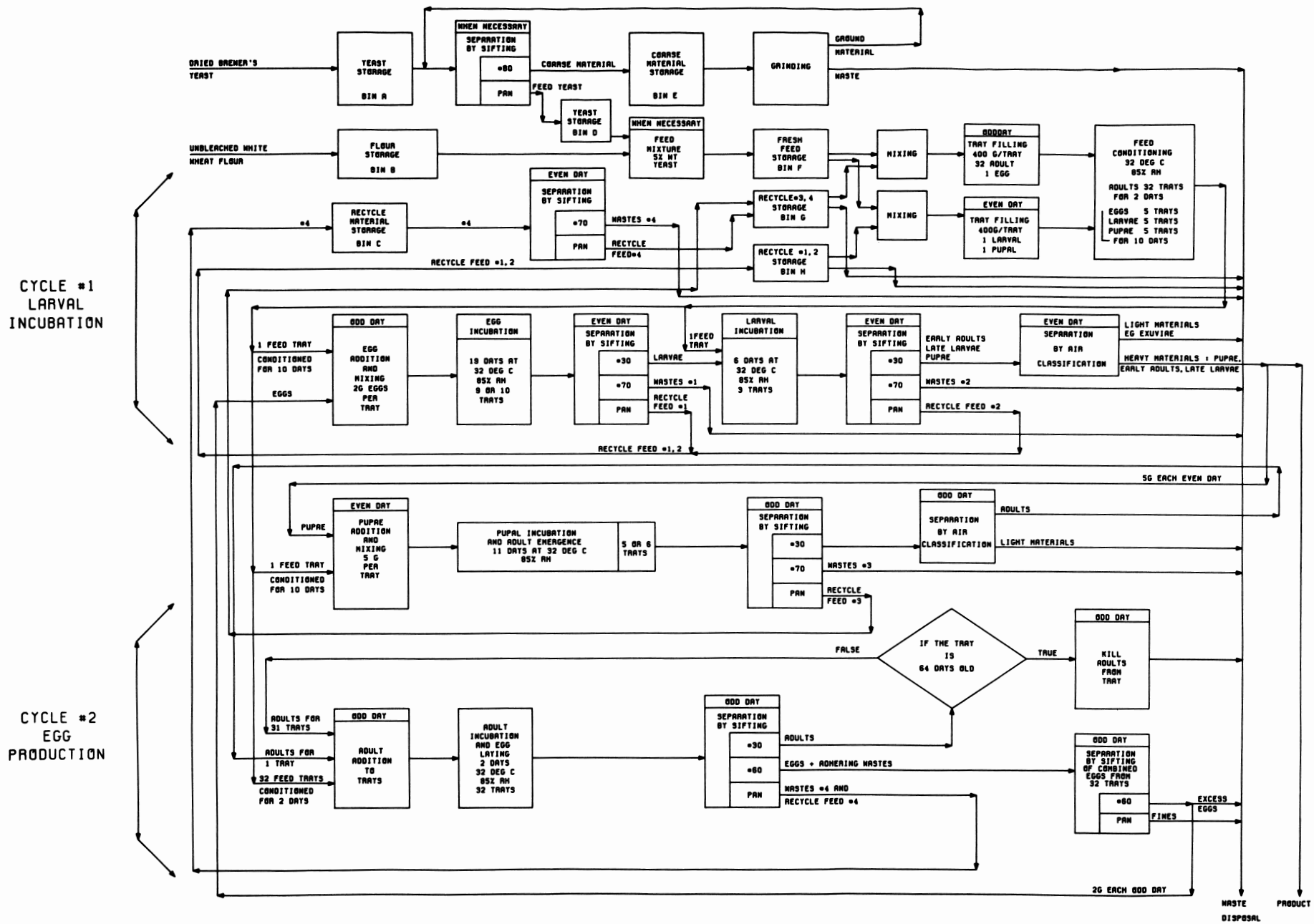

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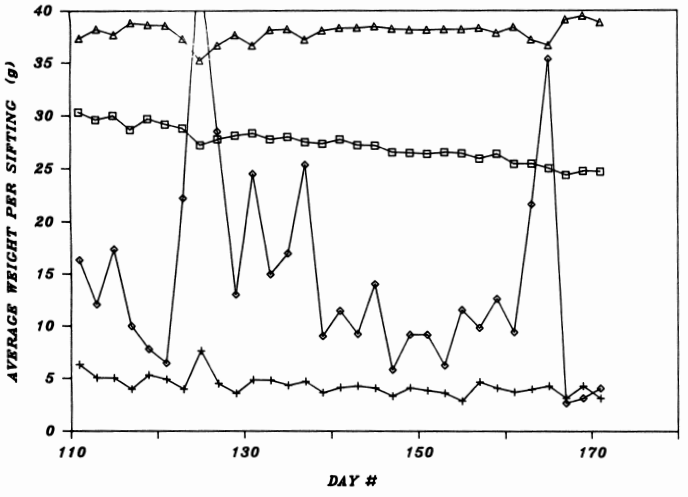

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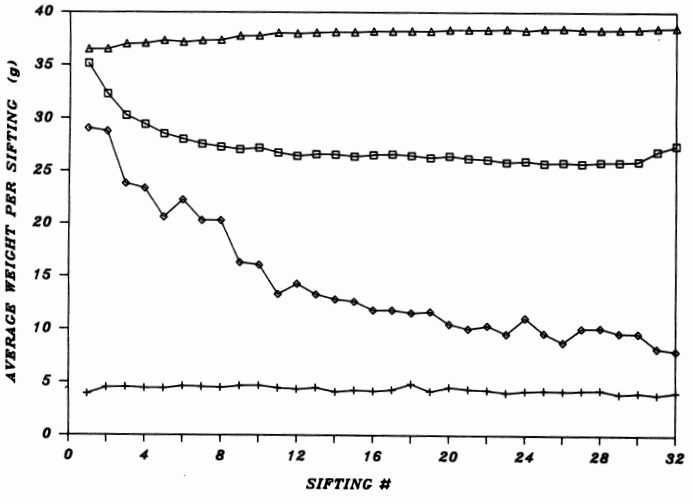

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