THE DESIGN AND FUNCTION OF FIELD DOMICILES AND INCUBATORS FOR LEAFCUTTING BEE MANAGEMENT *(MEGACHILE ROTUNDATA (Fabricius))*

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ABSTRACT

Factors causing mortality in the leafcutting bee *Megachile rotundata* during incubation and adult flight are discussed, especially as these are influenced by the structure of incubators and field domiciles. Designs of both incubators and field domiciles are provided and options for their use in environmentally different areas are outlined.

ACKNOWLEDGMENTS

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THE DESIGN AND FUNCTION OF FIELD DOMICILES AND INCUBATORS FOR LEAFCUTTING BEE MANAGEMENT *(MEGACHILE ROTUNDATA (Fabricius))*

W. P. Stephen

The alfalfa leafcutting bee, *Megachile rotundata* (Fabr.), was first reported as an efficient alfalfa pollinator in 1959, and because of its highly gregarious behavior was considered amenable to management (Stephen and Torchio, 1961). Initially, managed populations increased rapidly, with annual increases of two to three times where suitable nesting media were provided and an excess of alfalfa bloom was available. Within a few years, various producers had built up enormous local populations for alfalfa pollination.

By the mid-1960s the large, densely aggregated populations became hosts for a series of parasites *(Monodontomerus* spp. and *Tetrastichus* spp.) and nest depredators* *(Trogoderma, Tribolium)* and by the late 1960s many producers found it difficult to maintain bee populations at their earlier levels. The increase in pest problems prompted some growers to adopt prophylactic practices to minimize losses, but prophylaxis was neither religiously practiced nor rigidly followed on a seasonal basis.

An additional factor in the decline in the annual rate of increase of the leafcutting bee is the locally high incidence of unconsumed pollen masses — generally referred to as "unexplained mortality." A cell is constructed and provisioned by the bee and an egg is laid on the surface of the pollen. However, rather than developing, either the egg or young larva dies. Over the years, this mortality has been attributed to a variety of causes including population inbreeding (Eves and Johansen, 1973), pesticide residue (Waller, 1969), saponin content of alfalfa leaves (Thorpe and Briggs, 1972) or jarring eggs and young larvae from the surface of the pollen during midseason movement of domiciles. Although contributory, none proved to be of great significance.

Background Studies

It has been shown that both eggs and young larvae are very susceptible to short exposures at high temperatures (Undurraga, 1975). Recent laboratory studies have indicated that all immature stages of the bee from eggs through pupae are killed by as little as a 15-minute exposure to in-cell temperatures of 50°C (122°F) (Undurraga and Stephen, 1980a, and unpublished data). Temperatures within cells in both straws and boards** have been monitored in field domiciles having an eastern exposure. Thermocouples were inserted directly into tunnels which had been completed the previous day. Holes were drilled through the backs of the straw-filled box and a solid back board and thermocouples were positioned in each tunnel so one was in the bottom cell and the other in the top cell just beneath the leaf cappings. Temperatures were recorded on a continuous strip recorder. An additional thermocouple was placed in a protected position beneath the domiciles to monitor ambient temperature. Temperatures recorded from the top and bottom cells in tunnels of wood and straw in one of the domiciles (Nyssa, Oregon) for one day (July 25, 1972) are graphed in Figures 1 and 2.The temperature in the top cell of the straw reached 59°C (138°F) at 10 a.m. and was more than 50°C (122°F) for approximately two hours. The wood, on the other hand, provided better insulation to the cells; the maximum temperature in the top cell did not exceed 42°C (108°F). The in-cell temperatures in the bottom cells of wood and straws were similar and close to that of ambient air, reaching a maximum of 38°C (100°F) at 2 p.m.(Figure 1). As mortality is also a function of the duration of high temperature, calculations were made on the number of hours that the in-cell temperatures in wood and straws exceeded 21°C (70°F), 27°C (80°F), 32°C (90°F), etc., for two days, July 25, 1972, and August 6, 1972 (Table 1). On these two days, the lethal temperatures in the straws (more than 49°C = 120°F) occurred in the top cells for more than two hours. On warmer days, temperatures more than 50°C (122°F) have been recorded from top cells in both wood and straws when the media are exposed to the direct morning sun. Even in the late afternoon, bottom cells in boards backed directly against a 3/8-inch plywood sheet, the west wall of a domicile, have registered temperatures in excess of 50°C (122°F) (Table 2).

* A distinction is made in this paper between the true parasites, *Monodontomerus, Tetrastichus,* etc., which feed on and mature in or on the host, and nest depredators, *Trogoderma, Tribolium, Trichodes,* etc., which feed on bee provisions, leaves, bee larvae, or any other organic matter in their path.

** Refers to both "solid boards," in which holes are drilled into but not through a 120 x 15 x 7 centimeters (4 feet x 6 inches x 3 inches) wooden block, and "punch-out" boards of the same dimension but with holes passing through the block. The comments are equally applicable to laminated wood and polystyrene media.

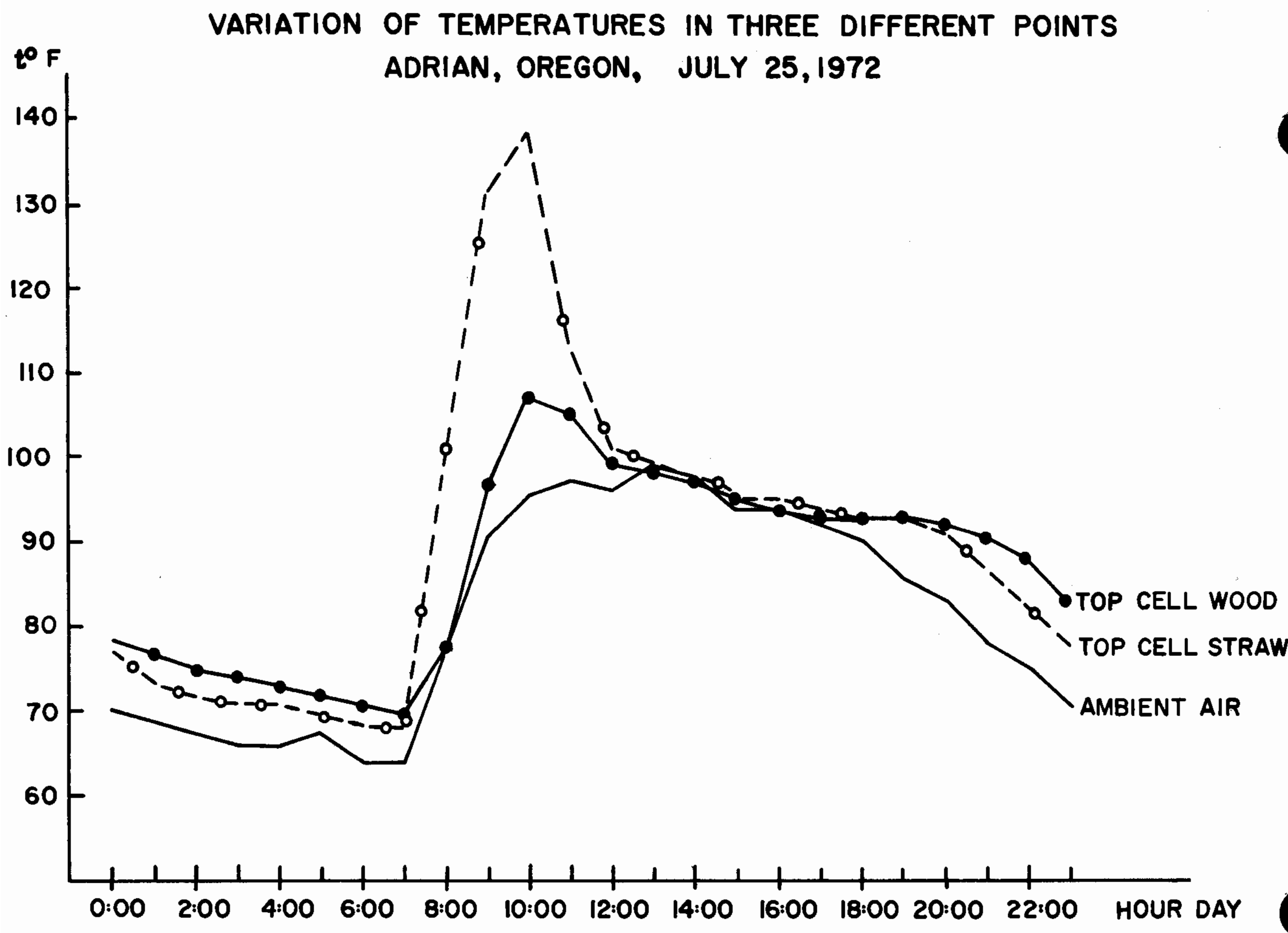

Figure 1. Temperatures within the top cells of capped series in paper soda straws and wood. July 25, 1972. Adrian, Oregon.

Table 1. Number of hours temperature exceeding 27°C (80°F) in straws and boards, Adrian, Oregon 1972

July 25, 1972	27°C (80°F)	32°C (90°F)	38°C (100°F)	43.5°C (110°F)	49°C (120°F)	54.5°C** (130°F)
Ambient*	12:15	9:05				
Board						
-Bottom cell	13:30	11:10	0:45			
-Top cell	15:40	12:45	2:30			
Straws						
-Bottom Cell	14:20	12:00	0:15			
-Top cell	14:50	12:45	4:05	2:50	2:15	1:35

* Ambient Max. 43.3°C (110.0°F) (13:30).
Ambient Min. 17.2°C (63.0°F (5:50).

August 6, 1972	27°C (80°F)	32°C (90°F)	38°C (100°F)	43.5°C (110°F)	49°C (120°F)	54.5°C** (130°F)
Ambient*	11:40	9:30				
Board						
-Bottom cell	12:50	10:15	1:20			
-Top cell	13:30	11:15	1:15			
Straws						
-Bottom Cell	13:15	11:05	1:15			
-Top cell	13:25	11:50	3:40	2:40	2:00	1:30

* Ambient Max. 37.5°C (99.5°F) (13:30).
Ambient Min. 13°C (55.5°F) (5:45).

** Temperatures in °C are rounded to the nearest 0.5°.

Table 2. Temperatures in leafcutting bee cells in nesting media located against west wall of domicile covered with 3/8 inch plywood, Lovelock, Nevada, 1972

Nesting Medium	Cell Position	Temperature °C	Temperature °F
Boards 6.4 mm holes	Top	42.2	107.9*
	Bottom	50.3	122.5
Straws 6.2 mm holes	Top	40.6	105.1**
	Bottom	48.9	120.0

* Ambient temperature 39.2°C (102.6°F) 17:00 PDT.
** Ambient temperature 38.3°C (100.9°F) 17:15 PDT.

Midsummer temperatures in the Snake River Valley of Oregon and Idaho, the warm valleys of Nevada, and the interior valleys of California often reach 43°C (110°F). In these areas it is essential that field domiciles provide protection from the sun to minimize heat-associated mortality.

Other areas in western America where alfalfa seed is grown and leafcutting bees are propagated have a generally cool climate (northern latitudes) or long cool nights and short hot days (higher elevations). See section on *Qualifications* (p.12). In these latter zones, the tempera-

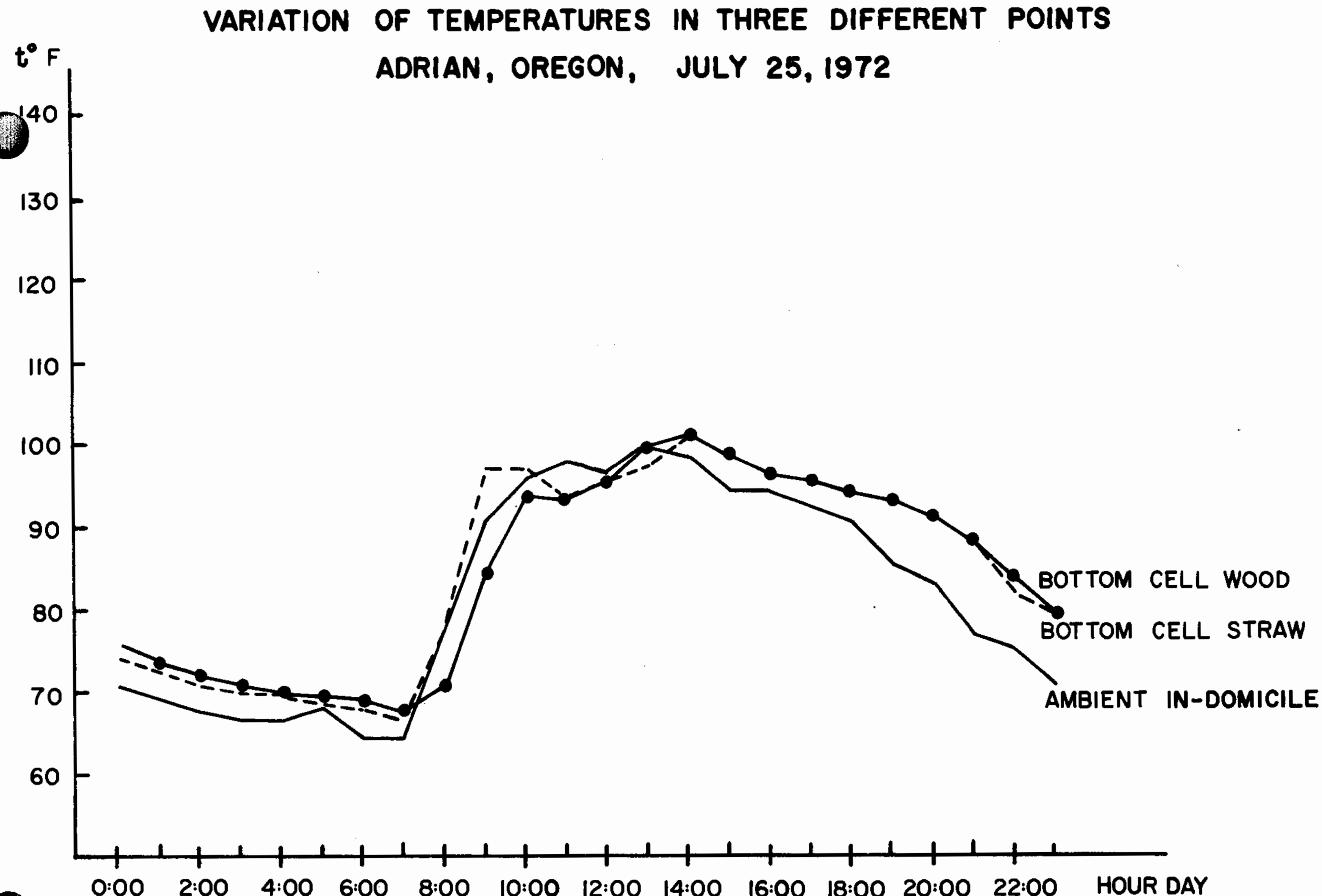

Figure 2. Temperatures within bottom cells of capped series in paper soda straws and wood. July 25, 1972. Adrian, Oregon.

ture in a conventional domicile fitted with an opaque awning (Figure 3a) increases very slowly and bee flight does not begin until late morning. The late onset of flight activity is often coupled with a temperature drop in late afternoon, and bee flight activity may be confined to no more than four hours per day. Protection of the nesting materials from wind and rain is still essential, but provision must be made to foster a rapid early morning temperature rise and to maintain the in-domicile temperature at, or above, the flight threshold of the bee for at least eight hours per day. The problem can be resolved by replacing the opaque awning and even sections of the roof with translucent fiberglass (Figure 4a, 4b).

Unusually cool years with temperatures suboptimal for bee activity also may be encountered in usually mild seed-producing regions. In recent years, many Pacific Northwest producers have suffered severe bee losses because of a week to 10 days of cool and/or rainy weather in mid- to late June. Bees already in flight will starve if they are unable to feed during these inclement periods. Thus, the producer should be able to provide full shade or open sun to the nesting medium to counter the excessive heat of mid-summer and the unusually cool periods of spring and fall. This can be accomplished by hinging the awning to the front edge of the roof of the domicile so it may be lowered to provide shade or folded back over the roof to maximize in-domicile temperatures (Figure 4c).

Since 1975, chalkbrood has been the major limiting factor to propagating the leafcutting bee, with losses from the disease exceeding 60 percent in some localities (Stephen and Undurraga, 1978; Stephen *et al,* 1981). Although the etiology of the disease is now fairly well known, prophylactic measures still appear to be the most effective means of limiting the disease. The structure of the domicile plays a major role in bee management, providing protection from the excessive heat and humidity, both of which may influence the incidence of chalkbrood. Short exposures of developing larvae to high temperatures not only result in high mortality but also stress the larvae, making them more susceptible to chalkbrood.

In 1976, boxes of straws were set out in a densely populated domicile on July 9. On July 15, they were removed from the field to the laboratory where completed tunnels were extracted and placed in an incubator at

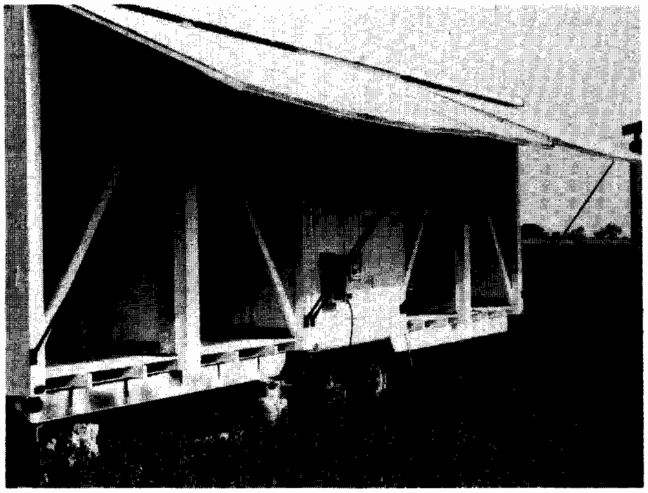

Figure 3a. Field domicle with incubator located medially and 4 nesting chambers approximately 6 x 8 feet.

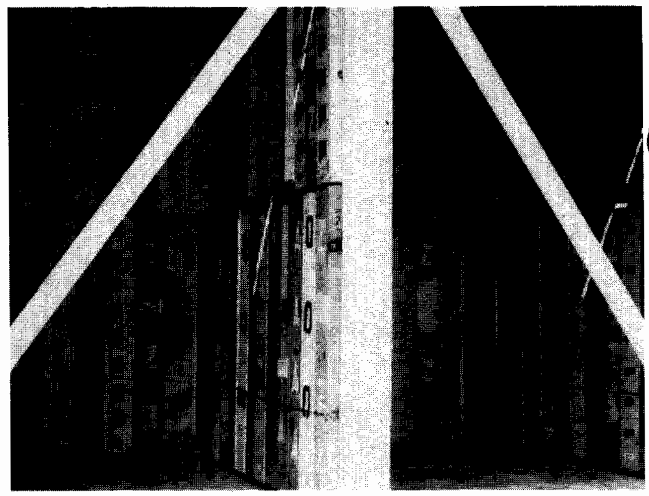

Figure 3b. Chambers of domicile in Figure 1a fitted with boards for bee nesting.

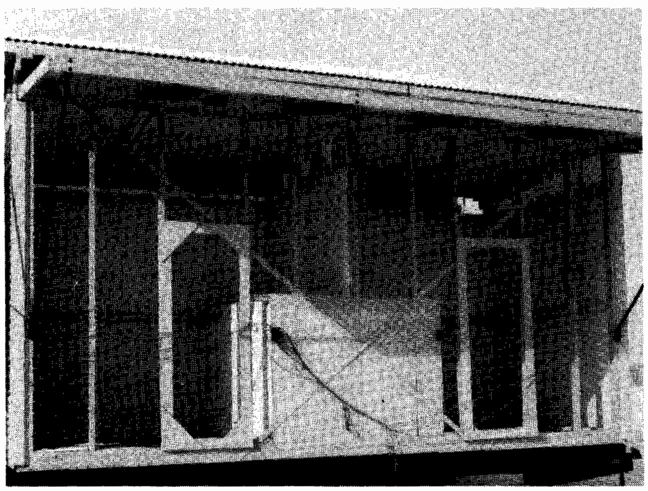

Figure 3c. Field domicile with incubator located in lower middle section and with 2 nesting chambers approximately 8 x 10 feet.

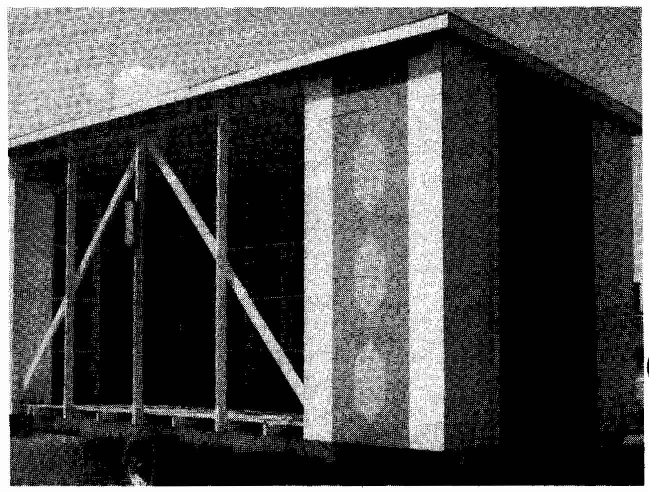

Figure 3d. Field domicile with incubator located at one end and with a single large nesting chamber approximately 8 x 16 feet.

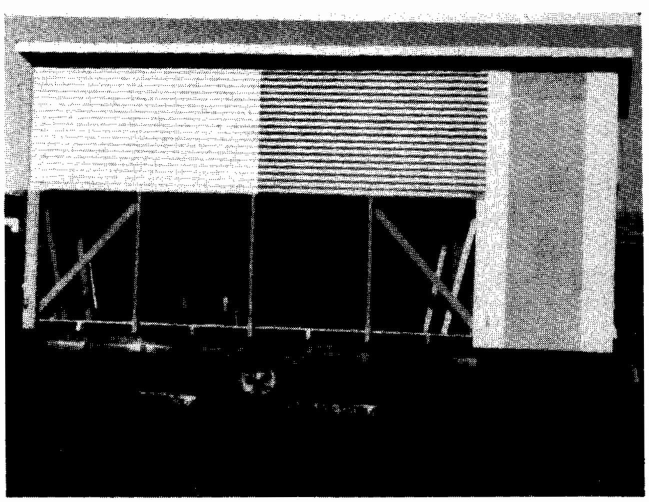

Figure 4a. Domicile identical to that in Figure 3d, but with upper frontal surface covered with fiberglass to promote higher in-domicile temperatures.

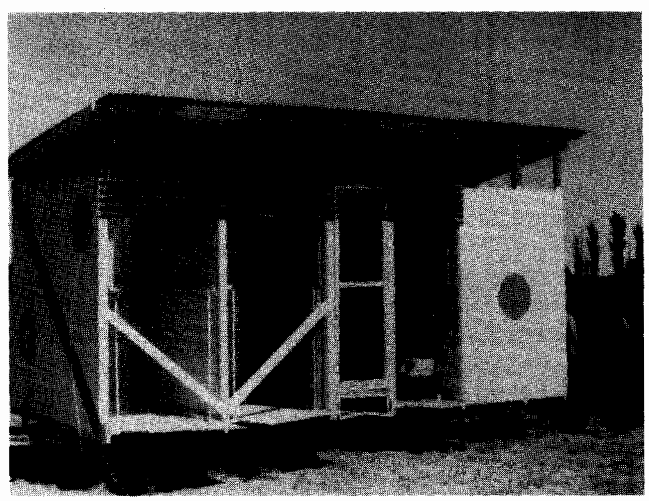

Figure 4b. Domicile with self-contained incubator utilized in southern Argentina with translucent fiberglass covering one-third of roof and the upper frontal surface.

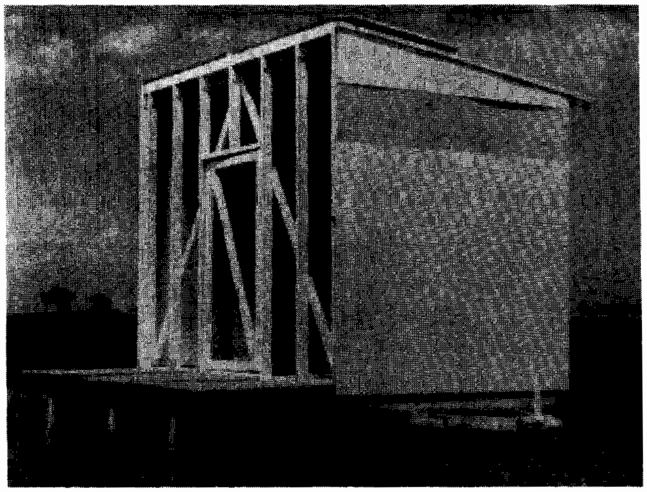

Figure 4c. Domicile with plywood awning folded back over roof. Folding landing platforms in front serve as sunning areas for adult bees during cool sunny weather.

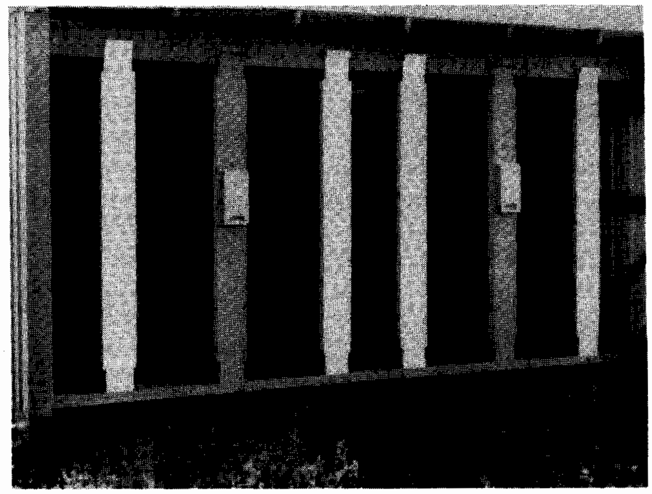

Figure 4d. Domicile lacking awning, with boards placed back-to-back in horizontal rows approximately 18 inches apart.

30°C (86°F). After 90 hours at 30°, all the eggs had hatched so the straws contained only developing larvae between the first and fourth instars. Two groups of straws were then pretreated at 7.2°C (45°F) and 20°C (68°F) for two days (to simulate a cool, wet period), brought to room temperature and exposed to 42.5°C (108°F) or 45°C (113°F) for one-half hour. All straws were then returned to 30°C (86°F) for two weeks to permit surviving larvae to complete development and cocoon spinning. A third group of straws was kept at 30°C (86°F) for two days and subsamples given half-hour exposures to 42.5°C (108°F) or 45°C (113°F) and then returned to 30°C for incubation. All straws were X-ray analyzed within three weeks after heat treatment (Stephen & Undurraga, 1976) and live larvae, dead fourth and fifth instar larvae, dead first through third instar larvae, and chalkbrood incidence recorded. The data are presented in Table 3. Pretreatment at 7.2°C and 20°C had no effect on larval survival nor the incidence of chalkbrood, nor did the one-half-hour exposure to 42.5°C (except in the mortality of early instar larvae in the 7.2°C sample). This is not surprising, for during the

Table 3. Effects of short periods of high temperatures on larval mortality* and chalkbrood incidence in the leafcutting bee, Oregon Slope, Oregon, 1976.

	Total Cells	% Live Larvae	% Dead Late Larvae	% Dead Early Larvae	% Chalk-brood
7.2° (2d) - 30°** (control)	341	61.3	11.4	7.0	5.3
7.2° (2d) - 42.5°(0.5h)-30°	135	56.3	9.6	21.5	9.6
7.2° (2d) - 45° (0.5h) -30°	118	1.7	11.0	59.3	21.2
20° (2d) - 30°C (control)	342	70.2	15.2	10.5	9.9
20° (2d) -42.5° (0.5h) -30°	143	60.8	16.1	9.1	11.2
20° (2d) - 45°(0.5h) - 30°	175	2.3	28.6	41.1	27.4
30° (2d) - 30° (control)	122	71.3	9.8	3.3	9.8
30° (2d) - 42.5°(0.5h) -30°	133	81.2	8.3	6.0	0.7
30° (2d) - 45° (0.5h) - 30°	143	0	46.9	25.2	27.3

* Mortality does not include parasitism or predation.
** Temperatures all in °C.

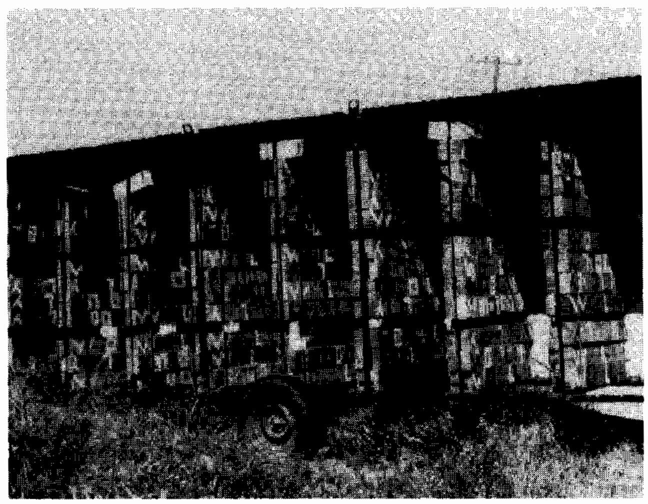

Figure 4e. Lightweight, highly mobile domicile with boards placed back-to-back in rows approximately 2 feet apart.

summer months developing larvae often are exposed to these extremes. However, the one-half-hour exposure to 45°C (113°F) killed most of the developing larvae directly and resulted in a nearly three-fold increase in chalkbrood.

It is difficult to dissociate the effects of temperature from those of humidity on larval mortality because both tend to be considerably higher at temperatures more than 40° (104°F) in poorly ventilated domiciles than in those which are well ventilated. However, in 1976, the summer was unusually cool with temperatures exceeding 38°C (100°F) on only three days. High temperature was not considered to be a critical factor in protected domiciles with southern exposure. Populations from a common stock of cells were established in a well ventilated and in an unventilated domicile at Nyssa, Oregon. At the end of the first generation, samples were taken from the upper and mid-sections of each domicile and analyzed for live larvae, chalkbrood, dead eggs, and larvae. If heat alone was the cause of mortality, the samples taken from near the domicile roof should have had the highest incidence of disease, dead eggs, and larvae, especially in the unventilated domicile. There was no significant difference among the samples taken from within each domicile, but disease, dead eggs, and larvae were higher in the unventilated (Table 4). The test was repeated in 1977 with one unventilated and two well-ventilated domiciles using a common bee stock for all. The summer temperatures were more typical of that area with eight days in excess of 43°C (109°F). The mortality in samples taken at the end of the first generation was much higher in the unventilated than the ventilated domiciles (Table 4). In the absence of high temperatures in 1976, the high disease incidence is attributed largely to high humidity in the unventilated domicile, whereas, in 1977, high overall mortality was considered to be an additive effect of both high temperatures and humidity.

Table 4. Mortality associated with ventilation in large domiciles. Nyssa, Oregon, 1976-1977

				Percent Mortality*	
Year	Domicile	Total Cells Sampled	Percent Live Larvae	Eggs & Larvae	Chalk-brood
1976	Ventilated	1607	77.5	10.6	9.3
1976	Unventilated				
	a) Upper section	203	60.1	17.3	20.2
	b) Mid-section So.	215	57.7	15.9	25.1
	c) Mid-section E.	180	62.2	13.3	21.1
1977	Ventilated I	668	81.0	13.9	5.1
	Ventilated II	424	81.4	12.5	6.6
	Unventilated	245	39.8	37.2	17.1

* Mortality does not include parasites or partial cells.

Since the microenvironment within the domicile can be modified to enhance bee activity and larval survival, and since incubation of either loose cells or cells in solid nesting media is essential to good population management, the type of field domicile and incubator has a direct bearing on the effectiveness of a seasonal bee management program.

Domiciles

The field domicile and its construction should be a major consideration for each producer in developing a management scheme. The domicile must be integrated into a phase-out program for diseased or parasitized materials, be accessible to bees emerging from an incubator in which the cells are placed, and provided nesting media with adequate protection from the sun, rain, and/or excess humidity.

Size of Domicile. Shortly after the leafcutting bee was domesticated it was recommended that small domiciles be constructed (10,000 to 40,000 holes) and that these be located in and around the fields to be pollinated (Stephen, 1962). This recommendation was based on the observed preference of the bee to work alfalfa in close proximity to the domicile, and the then prevalent idea that females would not forage more than a few hundred feet from their nesting site. Although females usually forage on the closest available bloom, it is now known that they fly more than one fourth mile from the domicile without abandoning the site. The distance they forage, without becoming lost or drifting, appears to be directly related to the domicile size. That is, large domiciles that are distinctively painted are markers on which the bees can orient readily. Small field domiciles scattered through the field are poor orientation markers and cause confusion among foraging females. Further, where there are many small domiciles in a limited area there is a tendency for nesting females to abandon those least populated and drift to those with stronger nesting populations. It is assumed that females are attracted to those sites in which the aggregating pheromone released by nesting females is strongest.

Thus, field domiciles should be sufficiently large and distinctively marked to be good orientation sites for foraging bees. Each nesting population should be large enough to maintain the integrity of that site (minimum of 20,000 nesting females in 60,000 to 80,000 nesting holes). Large domiciles (200,000 to 400,000 nesting holes with 50,000 to 100,000 females) should be mobile to permit moving them within the field or, from one field to another when forage is limiting, or when a highly toxic pesticide must be applied. As a rule of thumb, there should be three to four available nesting tunnels for every nesting female. At this ratio the females will be distributed evenly in the nesting media in a domicile, and this density of bees will assist in providing control of certain parasites, especially *Sapyga* (Undurraga and Stephen, unpublished data).

A compromise must be made by the producer between the rapidity with which he wishes to pollinate a given field and the increase he wishes to obtain in his bee population. Large bee populations may be moved into a field at or near full bloom and pollination can be achieved in 10 to 14 days. Rapid pollination through overpopulation creates intense competition among the bees for forage and large local populations (200,000 females) in each domicile result in disorientation and confusion in front of the nesting medium. Thus, the alfalfa seed producer must weigh the benefits of rapid pollination against the need for maintaining or increasing his bee population. In areas where early fall rains are common, a loss in the bee population may be justified if a seed crop can be pollinated and harvested before the end of August. Where possible, seed producers in the Pacific Northwest should compromise between intensive pollination and maximizing bee increase by having moderately sized domiciles (with 80,000 to 100,000 females) at sites with adequate bloom to support them for about three weeks. We recommend the use of domiciles of sufficient length (20 feet = 6 meters) and height (10 feet = 3 meters) so as to serve as a distinct landmark on which their nesting populations may orient (Figures 3,4).

Domicile size and structure will determine the extent of air circulation and ventilation that will occur around the nesting material. Good air circulation with air interchange is vital to keep in-domicile temperatures at or below those of the ambient air. High temperatures (38°C (100°F)) not only contribute to egg and larval mortality, but are believed to stress developing larvae and thus foster the development of chalkbrood. There is conclusive evidence that chalkbrood, as well as the saprophytic fungi, *Aspergillus* and *Penicillium* (especially where polystyrene plastic laminates are used) are more prevalent where in-domicile humidity is high (Richards, 1978). This condition can be minimized by providing adequate ventilation.

Our tests have shown that in domiciles with an interior height and depth of approximately 2.4 meters (8 feet), and a chamber size of 1.8 x 2.4 meters (6 x 8 feet) (Figures 3a, 3b), temperatures will be maintained from 5-8°C (9-14°F) cooler than ambient temperature. The difference between domicile and ambient temperature is greater in hotter weather, averaging 6°C (11°F) when the ambient temperature is more than 38°C (100°F).

Ventilation is equally important in cooler areas when fiber glass is incorporated into the domicile roof and/or used on the upper face of the domicile to foster an earlier and more prolonged daily flight period. An air space of 15 to 25 centimeters (6 to 10 inches) between the roof and wall sheeting prevents extreme temperature and humidity fluctuations.

Basic Elements of a Domicile: A domicile design, regardless of its size or mobility, should incorporate the following basic features:

1. Protection of the nesting media from the direct sun: This is best accomplished in domiciles with a 30 to 45 centimeters (12 to 18 inch) roof overhang on all sides; sufficient depth to the domicile so the nesting media can be protected from sun, rain, and wind; an awning to provide shade (Figure 3a) or a fiberglass facing in cooler climes to promote earlier flight activity (Figures 4a,4b) and by facing the domicile south or southeast.
2. Optimal ventilation to minimize in-domicile temperatures and humidity: As mentioned above, larger domiciles have better air circulation and are more readily ventilated. In addition, there should be an open air space of 10 to 20 centimeters (4 to 8 inches) between the sides of the domicile and the roof to promote air circulation. This air space must be screened with one-inch chicken wire mesh to prevent the entry of birds. A floor in the domicile, elevated about 60 centimeters (2 feet), is desirable because it reduces humidity originating in the plant growth beneath the domicile, reduces day-night temperature extremes in the domicile, and makes possible cleaning and decontamination of chalkbrood spores. Where intervening walls are used to accommodate additional nesting media in large domiciles these walls should extend only to within a foot of the rear of the domicile so they will not impede air circulation or movement of bees (Figure 5a).
3. Double-walled construction: The domicile diagrammed in Figure 5a has 2 x 4-inch studs and rafters, with inner and outer walls of 3/8-inch plywood, or with inner plywood and outer colored corrugated steel to form a double wall. In warmer areas, lethal temperatures (more than 49°C (120°F)) may be reached in the bottom series of cells in either boards or straws when the nesting medium is flush against the inside wall of a domicile covered with a single sheet of plywood. Such temperatures are common in nesting materials along walls struck directly by the afternoon sun. Our tests indicate that the double walls with an air space are as effective as the insulated wall in reducing temperatures to non-hazardous levels.
4. Nesting media and their arrangement: The domiciles illustrated can accommodate several media for bee nesting (Figures 3a, 3c — boards; Figure 3d — soda straws). The nesting media are located about the interior walls (Figures 3b, 3d) or against both sides of any intervening walls (Figure 3b) in all but two of the domiciles figured (Figures 4d, 4e). In the latter the boards are placed back to back and stacked horizontally from floor to roof in rows spaced from 50 to 75 centimeters (20 to 30 inches) apart. When the intervening space between adjacent rows is less than 60 centimeters (2 feet) problems in bee orientation are created which results in poor tunnel fill in the medium and generally in fewer cells per tunnel than in a medium more widely spaced and on which the bees are better able to orient. Given a comparable ratio of one female per four nesting tunnels, that female will produce fewer cells during a season in domiciles in which nesting medium is closely packed, than will one nesting in a medium in which orientation is not a problem.
5. Mobility: We recommend that all field domiciles be mobile to enable the bees to be moved rapidly during the night from a well-pollinated field to another just reaching full bloom, or from fields to which a toxic chemical must be applied. Where intensive pollination is practiced through overpopulation, domiciles must be moved every 10 to 14 days, otherwise, the bees may starve or abandon the domicile in search of forage. The relative positions of the domiciles in the field should be programmed early in the season so movement is kept to a minimum and the amounts of forage per population are maintained near optimal levels. Jarring of the nests during movement may result in mortality of eggs and early larval instars.
6. Protection against birds: Severe losses have been experienced by producers in areas where large numbers of insectivorous birds occur. Bird problems can be especially serious during emergence when mating bee fall to the ground, or on cool days when adult bees sun themselves on or near the domicile. Since cool, wet periods commonly occur during emergence, some protection should be given the bees if birds are noticed about the domicile-incubator. Bees usually will settle on barren patches of unshaded soil in front of, or on the sunny side of, the domicile when cool. In this torpid state they are ready prey to birds. One or more

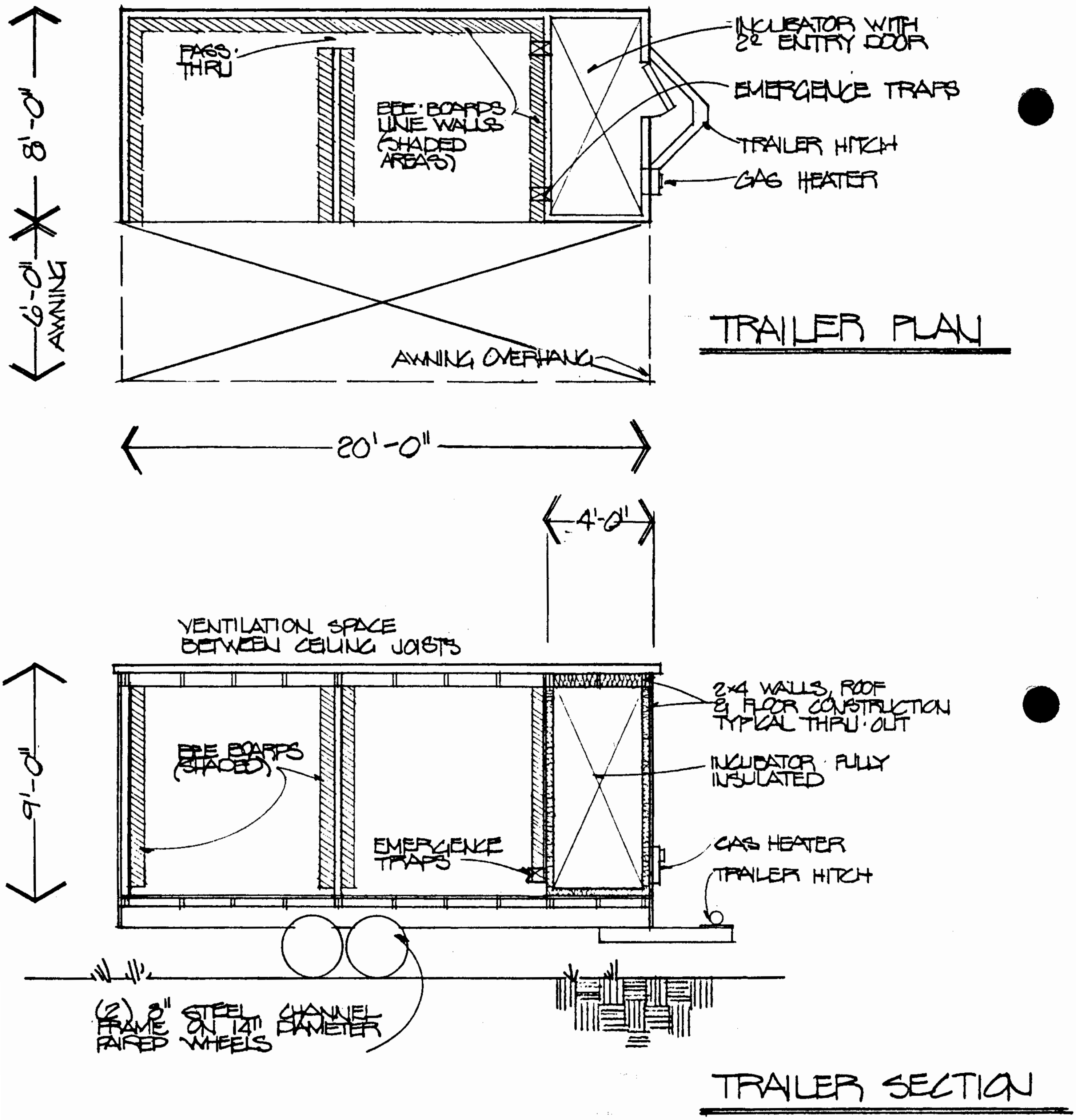

Figure 5a. Structural detail of field domicile with incubator at one end.

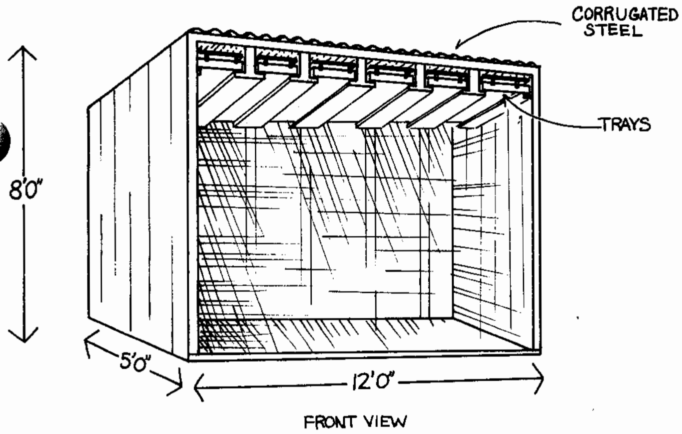

Figure 5b. Schematic of a field domicile in which trays containing cells are located directly beneath the corrugated steel or aluminum roof.

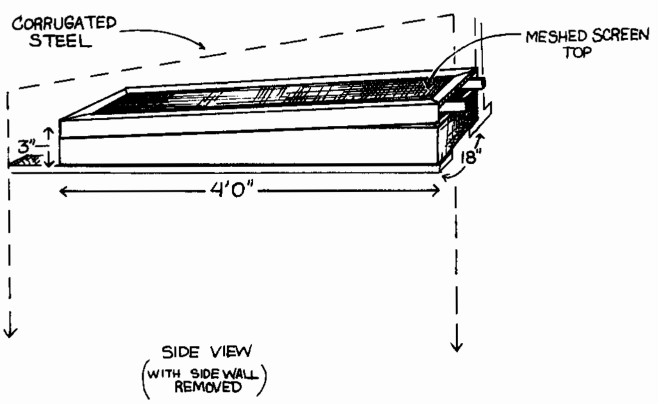

Figure 5c. Schematic of tray containing cells with the front propped open to permit egress of emerging bees.

widths of two-inch mesh chicken wire can be stretched over the critical areas at a height of 20 to 30 centimeters (8 to 12 inches) above the ground to provide some protection. Most of the bees will settle directly on the soil surface where they will be protected from foraging birds. Those that settle on the wire usually are disturbed by alighting birds and take to flight.

A number of birds species, including magpies, blackbirds, and, on occassion, woodpeckers, enter unprotected domiciles in mid-season and cause considerable destruction of soda straws and polystyrene laminates in search of bee larvae. Where such bird problems exist, the entire face of the domicile should be covered with two-inch mesh chicken wire and the upper ventilation space with one-inch mesh (Figure 3c, 3d). Foraging bees are often unable to see the wire and will often "bounce" off the strands while entering or leaving. We have no evidence that the wire significantly affects the rate of increase or the longevity of the adults in such domiciles, but in the presence of even small numbers of birds, the use of chicken wire is strongly recommended. A few of the smaller bird species, i.e., swallows, and starlings, occasionally will penetrate the two-inch mesh. However, a one-inch mesh should not be used on the face of the domicile unless the problem of bird penetration becomes severe.

Incubation and Incubators

The incubation of overwintered prepupae is the only certain way of synchronizing bee emergence with the bloom of alfalfa to be pollinated. It is also the most opportune time to control parasites and depredators and to initiate chalkbrood control practices. Incubation at 28 to 30°C (82-86°F) is essential to a loose-cell management system, but is equally beneficial in the management of cell in solid nesting materials. However, without the insulation provided by the board or laminate, loose cells are much more susceptible to the lethal effects of high or low temperatures and high or low humidity, and to parasitization than are cells in boards. Serious losses can occur during incubation if poor equipment is used or inadequate care given. There are a number of schemes which have been developed for loose-cell management (Stephen, 1981). The most successful include the incubation of cells to the completion of emergence. There still are producers who incubate loose cells at a central incubation site until male emergence reaches 25 to 50 percent and then transfer the trays containing the cells to a field domicile where emergence is expected to continue to completion. Because the cells must be protected from the lethal effects of direct exposure to the sun, the tray is placed in a well-shaded portion of the domicile and the cells covered with sawdust or vermiculite to prevent parasitization by endemic parasite species. If a series of cool days and/or nights follows their transfer to the field, the cells become chilled and only prolonged periods of unusually high temperatures will elevate the temperatures of these well-shaded cells above the 21°C (70°F) required for development and emergence. These cold periods are responsible for the high loose-cell mortalities (20 to 40 percent) which some producers have experienced, even though samples of cells taken from trays during incubation and transferred to the laboratory consistently had 95 to 98 percent emergence. Thus, we strongly recommend the use of a field management system with emerging bees held at or near a constant 30°C (86°F) until emergence is complete.

Further control can be exercised during spring emergence by equipping the incubator with a combination heater-air conditioner. An inexpensive, yet effective, means of heating and cooling a self-contained incubator of the size in Figure 6a, 6b (5 x 2.5 x 1.8 meters = 16 x 8 x 6 feet) is by means of an R-V air conditioner fitted with a heat strip. During incubation, the temperature in the incubator can be held between 28 to 30°C (85-88°F) or dropped to 15°C (60°F) should it be necessary to delay emergence. If it proves necessary or desirable to delay emergence after the incubator has been moved to the field, it simply can be pulled to a power source at night

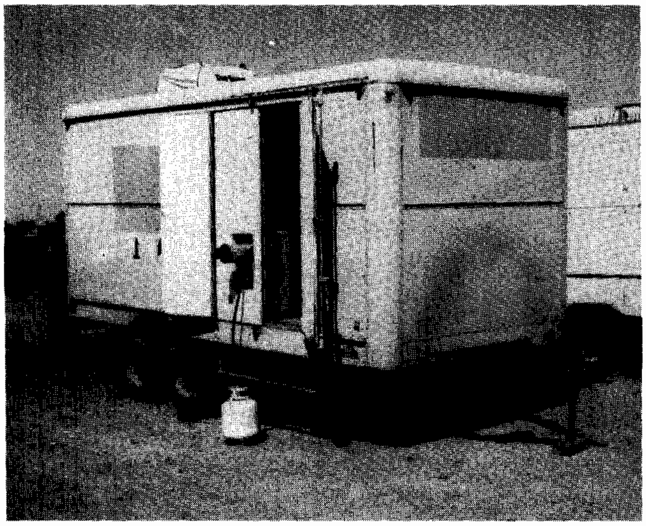

Figure 6a. Self-contained mobile incubator equipped with R-V air conditioner-heater (roof) and outside-venting gas heater for field use.

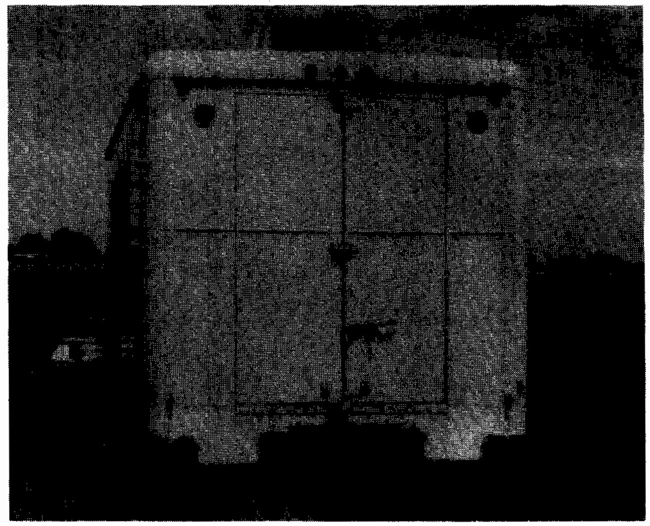

Figure 6b. Self-contained mobile incubator with emergence traps affixed to one side.

for refrigeration. Incubators may range in size from those meant to accommodate a few thousand cells to those designed for over 2,000 boards, but regardless of size, temperature control should be an intergral component. Weather during the last half of June in the Pacific Northwest is highly unpredictable, and should it turn cold for several consecutive days, bees will continue to emerge and die unless the incubator temperature can be adjusted to delay their development. Normally the incubator cannot be adequately cooled by opening the door at night to air it out because the metabolic heat generated by large numbers of developing larvae and pupae in a tray is sufficient to maintain temperatures at or above the threshold for development. With a suitable air conditioner, the interior of the incubator can be kept at 10 to 15.5°C (50 to 60°F), completely arresting development. Development and emergence can be delayed for up to seven days at any time during the emergence period, with no mortality, when the cells are held at the above temperature (Undurraga and Stephen, 1980b). Such control often can prevent drastic bee losses during inclement weather, or be used to delay bee emergence if alfalfa blooms later than anticipated.

Basic Elements of an Incubator

There are certain features which should be incorporated into all incubators:

1. All walls, floor, and ceiling of the incubator should be of double-wall construction and well insulated.
2. The interior of the incubator should be thoroughly sealed with caulking or stripping so that only light entering through the emergence traps will attract the bee and parasites to the exit. Competing light leaks will result in the loss of adults unable to find the trap exit and also will permit parasites and nest depredators to escape and reinfest cells of the new generation. Special care should be taken to seal the door well.
3. All incubators should be equipped with a light-tight ceiling ventilator (Figure 7a) which will provide limited but adequate air interchange. The oxygen consumption of several million larvae and pupae during peak metabolic periods is very high and in tightly sealed, unventilated incubators severe losses of emerging adults, and especially of developing pupae, have occurred because of a lack of oxygen. One or more traps fitted to the base of the incubator during incubation will provide adequate routes for air interchange.
4. The interior floor of larger incubators with only one or two emergence traps should be painted white to enhance the limited light entering through the trap. Painted surfaces also are more readily sanitized for disease control (Stephen and Undurraga, 1978; Stephen *et. al.*, 1981).
5. Racks to accommodate trays of loose cells or boards should be designed for each incubator and, where possible, the trays should be interchangeable (Figure 7a). Care should be taken in the design of the racks, allowing adequate space between the top of one tray and the bottom of the other (minimum of 4 centimeters = 1.5 inches Figure 7b) so that light will be visible to emerging bees and allow them to move toward the traps. Solid boards to be phased out must be provided with at least 1.25 centimeters (1/2 inch) space at their faces to permit emerging bees to orient to the light.
6. A six-to eight-inch clearance must be maintained between the floor of the incubator and the lowest tray so emerging bees and parasites fall directly into an open arena where light from the emergence trap can be seen (Figure 7b).
7. Phase-out or parasite traps must be attached to each incubator shortly after the beginning of incubation. One trap covering an opening of approximately 13 × 20 centimeters (5 × 8 inches) is adequate for each 37 meters^3 (400 feet^3) of incubator space (Figure 6b).

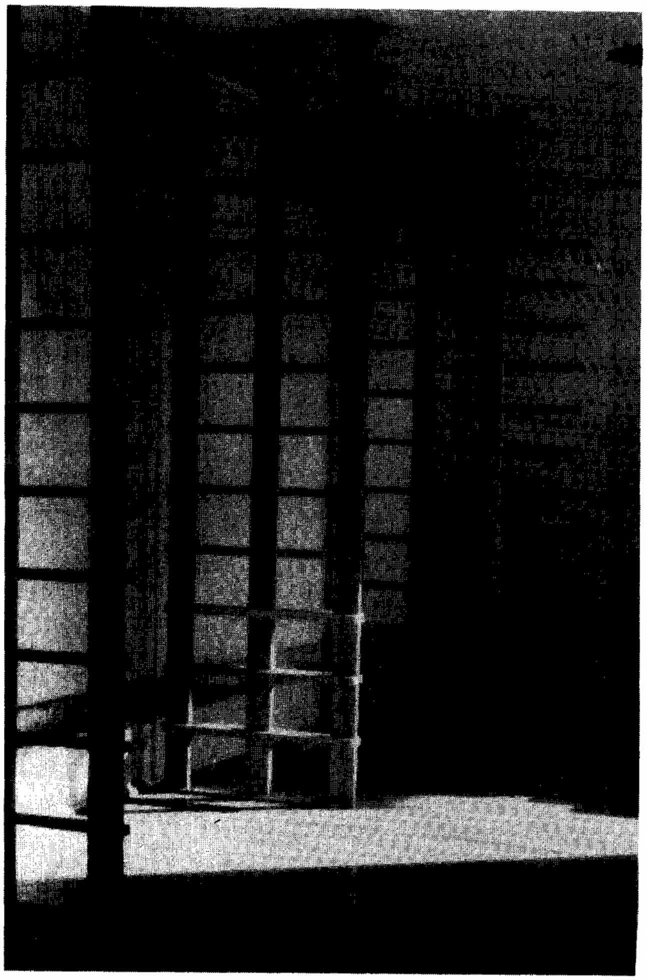

Figure 7a. Interior of mobile incubator fitted with removable racks to accommodate trays of bee cells. Blind ceiling vent can be seen on upper portion of photo.

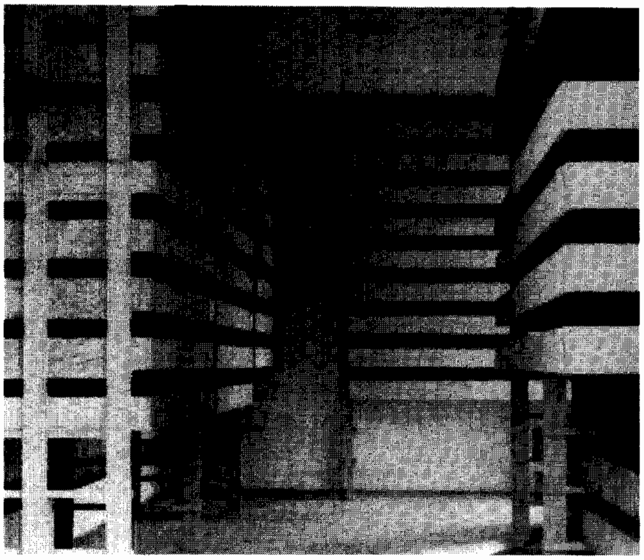

Figure 7b. Interior of incubator showing racks partly filled with trays containing bee cells, the spacing between trays and the open arena at floor level.

In-Domicile Incubators: Each of the domiciles shown in Figures 3a, c, and d has an incubator incorporated at one end, the middle or lower-middle section, and each incubator is insulated on all sides. The incubator is equipped with a thermostatically controlled outside-venting gas furnace* to maintain the incubating cells at a constant temperature. Care should be taken to purchase a heater with a high-quality thermostat, or the unit should be fitted with a second high-temperature cut-out. On occasions, growers have lost substantial portions of their bees because of thermostat malfunction which permitted the incubator temperature to rise beyond 50°C (122°F). An indoor-outdoor thermometer should be mounted on the incubator so interior temperatures can be read quickly, and the incubator should be monitored several times a day. We have found that the heater in a well-insulated incubator in the field can be turned on in the early morning, monitored for a few hours, and then turned off (or to "pilot") at noon. This usually warms the incubator sufficiently to promote good (but not necessarily maximal) daily bee emergence. Each incubator has from one to four emergence traps located so the bees emerge directly into the domicile in which the nesting media are housed.

Self-Contained Incubator: The size of a self-contained mobile incubator should be based on the number of bees (or bee boards) the producer has, and the number of field domiciles he expects to populate in a fixed period during late spring. The incubator shown in Figure 6a is 5 × 2.5 × 1.8 meters (16 × 8 × 6 feet) and can accommodate approximately 5 million loose cells or 650 boards. Each incubator can be equipped with an electric heater-air conditioner to maintain optimal interior temperatures. Further, as mentioned above, it can be returned to a power source for cooling if inclement weather calls for delaying bee emergence. Once in the field, a secondary heat source is needed for rapid and continuous emergence. This can be accomplished by using a thermostatically controlled outside-venting gas furnace fitted directly into the incubator body, or on a removable door as illustrated in Figure 6a. The heater should be carefully monitored (see above).

The mobile self-contained incubator may be kept at a single field site and the domiciles to be populated moved next to it, or, the incubator can be pulled adjacent to a field positioned domicile and moved after that domicile is adequately populated. If the incubated bees are heavily infected with chalkbrood, it is recommended that the incubator be kept at one position and the domiciles placed nearby. This will help confine much of the disease spore inoculum carried by emerging adults to the area about the incubator rather than distributing it from field to field.

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* An outside-venting gas heater must be used. Non-vented gas heaters consume free oxygen in the incubator and cause the death of developing larvae.

In the latter scheme, it is essential that the population in the domicile adjacent to the incubator be built up rapidly and the domicile moved to the field before the females become oriented to the emergence site. Normally newly emergent females require three to five days to become fully oriented to the nesting domicile. Only one, or at most two, domiciles should be available for emergent bees. Maintaining constant optimal temperatures in the incubator results in an accelerated emergence, and a large domicile (200,000 to 400,000 holes) can be adequately populated in three days. Once populated, the domicile can be moved and replaced with a second to accommodate the emergent bees of the following day. A large field domicile, well marked and distinctively painted, is a major land mark itself and aids in preventing drift after it has been moved.

A unique method to foster rapid bee development and emergence is employed by several producers in the high elevations near Orovada, Nevada. Cells are incubated in trays at a centralized incubator. When male emergence is underway, the cells are covered with an inch of coarse sawdust and each tray is fitted with a screened top (Figure 5b). The trays are then slid into prepared slots located immediately under the roof of the domicile and the "front" end of the tray is propped open slightly to provide the only site of egress for emerging bees (Figure 5c). The screen and the sawdust prevent infestation of the cells by endemic parasites. The roof, constructed of corrugated sheet metal, heats in the direct sun and acts as a radiant "heater" to the cells lying directly below it. This method, while lacking the precise control of either a fixed or mobile incubator, provides a practical means of forcing development of the cells when field incubators are not available.

Fixed Incubator

Effective incubating schemes centered about a fixed incubator have been developed by some producers in the Pacific Northwest and western Canada. These systems involve capturing the adult bees as they emerge and transporting them once or twice daily to field domiciles where they are to be established. The advantages of the fixed incubator scheme are that both temperature and humidity can be better controlled through back-up electrical thermostats, and more effective refrigeration can be incorporated into the system to delay development and emergence. Its principal disadvantages lie in the more complex collection procedures and in the time demands on the producer in monitoring, collecting, and transporting bees to the field at the appropriate time each day.

However, an elaborate fixed site incubation scheme is the *most* effective of all systems where parasties, disease, and unpredictable weather are problems. The system centers on a fixed incubator in which temperature and/or humidity can be controlled between 10 and 30°C (50-86°F). Emerging bees and parasites pass from the incubator through an emergence trap where the parasites are removed. The bees fall from the trap into a screen cage located in a chamber or room held at 10°C (50°F) and are quickly immobilized. Trays stocked with newly emerged bees can be kept for one to several days, or until good flight conditions exist, dipped in a surface decontaminant solution to inactivate chalkbrood spores and then released at the field domicile (details provided in Stephen 1981b). Although the system requires more complex facilities, it is less labor intensive than other systems and has the distinct advantage of maximizing control over bee activity (during incubation *and* emergence) and parasties, and provides the most effective means of chalkbrood control (Figure 8).

Qualifications: Domiciles, incubators, and management schemes must be developed for each zone in which the leafcutting bee is propagated. In the Pacific Northwest alone, seed alfalfa is produced in distinctly different climatic areas: some rarely if ever have frost after June 1, and experience periods of intense summer heat; others can expect frost at any time of the year and have summer temperatures which rarely exceed 32°C (90°F).

Outside the Pacific Northwest, the leafcutting bee is propagated in such climatically diverse areas as the Sacramento Valley of California, the northern portions of Saskatchewan and Alberta in Canada, and southern Argentina. It is apparent that a field domicile designed to protect the nesting population of bees from the intense heat of California (or some Pacific Northwest areas) is functionally inappropriate in northern Canada, or southern Argentina, where in-domicile temperatures must be enhanced to achieve maximal bee activity during the relatively short flight period. Thus, where morning temperatures are low and bees do not begin foraging until 10 to noon, an opaque awning should not be used and portions of the roof should be replaced with corrugated fiberglass or a comparable material to warm the interior by solar radiation (Figures 4a,4b). Shallower domiciles (1.2 meters - 4 feet deep) should be used in cool areas to permit a more rapid rise in temperature. In the very high elevations of the Pacific Northwest and at high latitudes,

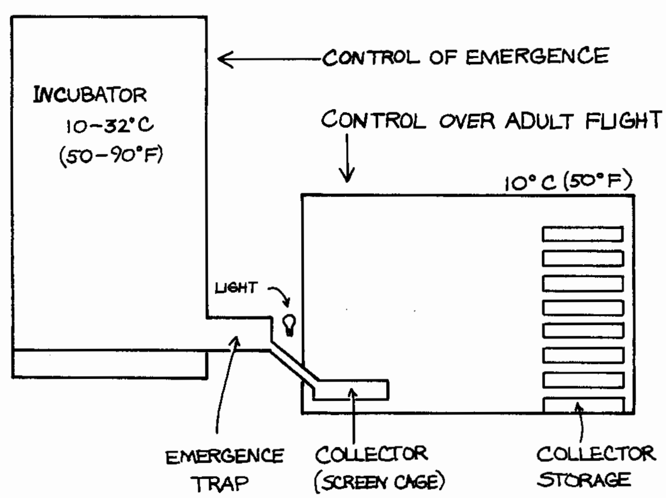

Figure 8. Schematic of a fixed incubation system in which the emergence can be controlled through variable incubation temperatures, parasites can be removed, adult bees can be kept inactive in caged screen for disease treatment.

domiciles should be oriented to face the morning sun, should provide protection from the wind and rain, and should be well ventilated to keep in-domicile humidity low. In general, the bee domicile should be designed to minimize temperature extremes to which bees and developing larvae are exposed, i.e., 15° to 32°C (60° - 90°F).

Framing covered with transparent polyethylene has been used to induce rapid rise of in-domicile temperatures in cool areas (Pankiw and Siemens, 1974). The practice is counterproductive because fragile polyethelene covers create extremes in temperatures—lower than ambient at night and much higher, bordering on lethal, on sunny warm days — in large domiciles. These temperature extremes in a vapor-tight barrier of polyethylene result in high in-domicile humidity, which, in turn, prompts the development of *Aspergillus* and *Penicillium*-type fungi in the cells.

Further, the type and size of the domicile also must be a function of the purpose for which leafcutting bee population is being propagated. The domiciles illustrated in this bulletin are designed to accommodate large, densely aggregated populations of the bee for alfalfa pollination. These populations are meant to achieve rapid pollination of a limited crop acreage, and because of their large numbers, bees may compete for both nesting space and available bloom. This competition may result in a reduced rate of increase in any given generation of the bee. Domiciles intended to accommodate a leafcutting bee population for expansion only should be small, fixed in a position to avoid orientation problems, and located where forage is superabundant.

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