POPULATION ECOLOGY OF THE AMERICAN COCKROACH, *Periplaneta americana* (L.) AND ITS POTENTIAL CONTROL USING PARASITOID *Aprostocetus hagenowii* (RATZEBURG) (HYMENOPTERA: EULOPHIDAE)

by

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ABSTRAK

Tesis ini bertumpu kepada ekologi populasi lipas Amerika, *Periplaneta americana* (L.), dalam sistem pembentungan. Selain itu, potensi penggunaan parasitoid ooteka lipas, *Aprostocetus hagenowii* (Ratzeburg), dalam pengawalan lipas Amrika juga dikaji dalam aspek meningkatkan kaedah pemeliharaan dan kawalan biologi terhadap lipas.

Ekologi populasi lipas Amerika telah dikaji di tiga sistem pembentungan di Kampus Minden, Universiti Sains Malaysia, Pulau Pinang daripada September 2008 hingga Oktober 2009. Imago and nimfa adalah aktif sepanjang masa kajian berdasarkan purata tangkap bulanan 57□97 imago dan 79□99 nimfa. Min keseluruhan perkadaran imago dan nimfa adalah 0.47 and 0.53 masing-masing. Perkadaran jantan dan betina yang bertanda tidak berbeza dengan perkadaran jantan dan betina yang bertanda dan ditangkap semula. Betina bertanda yang ditangkap (24.7%) semula direkod bergerak antara tangki pembentungan lebih kerap daripada jantan (19.4%). Majoriti (90.4%) jarak pergerakan lipas antara tangki-tangki pembentungan adalah dalam 2–20 m; satu jantan bergerak sejauh 190 m. Tangkapan lipas adalah berkadar langsung dengan min suhu harian manakala pergerakan lipas adalah berkorelasi dengan min suhu minima harian.

Kesesuaian ooteka yang dibunuh secara pemanasan dan pembekuan sebagai perumah untuk pemeliharaan *A. hagenowii* telah dinilai. Perkembangan embrio ooteka berumur dua hari boleh dihentikan melalui proses pembekuan atau pemanasan pada suhu □20°C atau ≥48°C selama ≥30 min. Kesan ooteka yang dibunuh secara pemanasan dan pembekuan ke atas beberapa parameter biologi *A. hagenowii* telah ditentukan. Peratus parasitisme, kadar penetasan dan masa perkembangan *A. hagenowii* dalam ooteka-ooteka yang dibunuh secara pemanasan dan pembekuan adalah tidak berbeza secara signifikasi berbanding ooteka-ooteka hidup. Kedua-dua pemanasan dan pembekuan tidak mempengaruhi bilangan progeny (jantan dan betina) dan nisbah seks *A. hagenowii* yang menetas daripada ooteka yang dibunuh.

Aktiviti kawalan biologi *A. hagenowii* telah dikaji di dalam rekahan sekitar bangunan dan di dalam tangki pembentungan selama 12 minggu dari Januari hingga April 2010 di Kampus Minden, Universiti Sains Malaysia, Pulau Pinang. Selain itu, kecenderungan *A. hagenowii* terhadap ooteka-ooteka yang berumur satu hingga empat minngu telah dikaji di dalam makmal. Min (± SE) mingguan peratus parasitisme ooteka-ooteka sentinel di dalam rekahan bangunan adalah 18.1 (± 3.2) % manakala min mingguan peratus parasitisme ooteka sentinel di dalam tangki pembentungan adalah 13.3 (± 2.0) %. Min (± SE) mingguan sebanyak 428 (± 50) ekor *A. hagenowii* betina yang diperlukan untuk memparasit satu ooteka sentinel telah dicatat dalam perlepasan yang dibuat ke dalam tangki pembentungan manakala min (± SE) mingguan sebanyak 189 (±18) telah didapati daripada perlepasan yang dibuat ke dalam rekahan bangunan. *A. hagenowii* betina adalah lebih berkesan memparasit ooteka sentinel yang diletak di aras tinggi dan tengah daripada ooteka sentinel yang diletak di aras rendah di dalam tangki pembentungan. *A. hagenowii* betina tidak menunjukkan kecenderungan terhadap umur ooteka.

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ABSTRACT

This thesis focuses on the population ecology of the American cockroach, *Periplaneta americana* (L.), in sewers. In addition, the potential of using an oothecal parasite, *Aprostocetus hagenowii* (Ratzeburg), in controlling American cockroaches was evaluated in the aspects of rearing improvement and biological control of the cockroaches.

Population ecology of *P. americana* were studied in three sewers in the Minden Campus of Universiti Sains Malaysia, Penang from September 2008 to October 2009. Adults and nymphs were active throughout the study period based on an average monthly trap catch of 57–97 adults and 79–99 nymphs. The overall mean proportion of adults and nymphs at the three sewers was 0.47 and 0.53, respectively. The proportion of marked males and females did not differ significantly from the proportion of recaptured marked males and females. However, the mean number of times a female was recaptured was significantly greater than that of males. Recaptured marked females (24.7%) were recorded moved more between manholes compared to that of males (19.4%). Majority (90.4%) of the cockroach movement made between manholes was within the distance of 2–20 m; one male moved 192 m. Trap catches of cockroaches were positively correlated with daily mean temperature while cockroach movements was correlated with the mean daily minimum temperature.

Suitability of heat- and freeze-killed oothecae of *P. americana* as hosts for rearing *A. hagenowii* was evaluated. Embryonic development of 2-d-old oothecae can be terminated by either freezing at □20°C or heating at ≥48°C for ≥30 min. The effects of heat- and freeze-killed oothecae on several biological parameters of *A. hagenowii* were determined. Percentage parasitism, emergence rates and developmental times of *A. hagenowii* in both heat- and freeze-killed oothecae were not significantly different from those of the live oothecae. Both heating and freezing did not influence progeny number (male and female) and sex ratio of *A. hagenowii* emerged from killed oothecae.

Biological control activity of *A. hagenowii* was evaluated in crevices around buildings and in sewer manholes for 12-wk from January to April 2010 at the Minden Campus of Universiti Sains Malaysia, Penang. In addition, preference of *A. hagenowii* for 1□4-wk-old oothecae was evaluated in laboratory. The weekly mean (± SE) sentinel oothecal parasitism rate in crevices around buildings was 18.1 (± 3.2) % while the weekly mean (± SE) sentinel oothecal parasitism rate in sewer manholes was 13.3 (± 2.0) %. A weekly mean (± SE) of 428 (± 50) released *A. hagenowii* females needed to parasitize a sentinel ootheca was recorded from releases made in sewer manholes while a weekly mean (± SE) of 189 (± 18) was obtained from releases conducted in crevices. *A. hagenowii* females were more effective in parasitizing sentinel oothecae placed at high and middle levels in manholes than that of low level when releases were made at the middle point in manhole shaft. *A. hagenowii* females showed no preference for any oothecal age.

CHAPTER ONE

GENERAL INTRODUCTION

The American cockroach, *Periplaneta americana* (L.) is an important species of insect pest in the urban environment. Besides leaving stains and an unpleasant odor, *P. americana* is a potential mechanical vector of various pathogenic organisms, and it contains allergens that may responsible for allergies and asthma (Roth and Willis 1957, 1960; Reuger and Olson 1969, Gore and Schal 2007, Rust 2008, Lee and Ng 2009). In Southeast Asia, *P. americana* is a predominant domiciliary pest cockroach, and it also is able to thrive in large numbers in outdoor environments such as sewers and bin chutes, where conditions are favorable for its development (Lee and Lee 2000, Lee 2007, Lee and Ng 2009).

Population ecology study is one of the fundamental steps to deal with pest cockroaches before any effective management strategy can be designed specifically to manage these insect pests that have well-adapted to human living environments. Studies on the *P. americana* populations in an outdoor environment around houses and in a green house has been conducted (Appel 1986, Coler et al. 1987). However, studies on the population ecology of *P. americana* in sewers is limited. American cockroaches are known to thrive in enormous numbers in sewers and these reservoir populations in sewers are responsible for their infestation indoor (Eads et al. 1954, Jackson and Maier 1955, 1961; Robinson 2002).

Cockroach management has relied heavily on insecticide application (Lee and Ng 2009). These management strategies commonly target on adults and nymphs, such as application of toxic baits and sprays that take effects when cockroaches come into contact and get a lethal dose (Rust et al. 1991, Smith et al. 1997). Integrating oothecal parasitic wasps into a conventional cockroach management program may further reduce cockroach population because of the ability of parasitoids to search for and parasitize oothecae which are either concealed or deposited in areas that require a thorough search for their locations (Rau 1943, Piper at al. 1978, Hagenbuch et al. 1989, Gordon et al. 1994a, 1994b; Yeh 1995, Bell et al. 1998).

Aprostocetus hagenowii (Ratzeburg) is a cockroach oothecal parasitoid with worldwide distribution. Its immature stages are developed entirely inside ootheca with nutrients obtained from consuming cockroach eggs. Many authors have reported its biology and behaviors in details (Cameron 1955, Edmunds 1955, Roth and Willis 1960, Lebeck 1991). However, information on method to improve its rearing is not extensively studied. Hagenbuch et al. (1988) demonstrated methods for mass-rearing *A. hagenowii* and its host, American cockroaches. Nevertheless, use of live oothecae for rearing *A. hagenowii* may contaminate rearing cages and requires frequent handling of hatching cockroach nymphs from unparasitized oothecae. In addition, use of killed-oothecae can prevent accidental releases of pest from unparasitized hosts during biological control program (Suiter et al. 1998). Therefore, the possibility of using killed-oothecae for rearing and field releases of *A. hagenowii* is worth to study to improve rearing and ensure a proper field release method.

A. hagenowii is suggested as a promising biological control agent against cockroaches (Cameron 1955, Roth and Willis 1960, Narasimham 1984, Lebeck 1991). Evaluation of the biological control potential of *A. hagenowii* in simulated-field conditions and in treehole microhabitats infested with blattid cockroaches demonstrated its excellent ability in controlling *P. americana* (Roth and Willis 1954, Hagenbuch et al. 1989, Suiter et al. 1998). However, evaluation of the biological control ability of *A. hagenowii* in around buildings and in sewers has not been evaluated in details.

Therefore, the objectives of this study are:

a. To study population ecology and movement of *P. americana* in sewers.

b. To evaluate the suitability of heat- and freeze-killed oothecae as hosts for rearing *A. hagenowii.*

c. To evaluate the biological control potential of *A. hagenowii* in controlling *P. americana* in crevices around buildings and in sewer manholes.

CHAPTER TWO

LITERATURE REVIEW

2.1 Biology of *P. americana*

The American cockroach, *P. americana*, is a pest cockroach with worldwide distribution. The generic name *Periplaneta*, which means to wander around, describes this *Periplaneta* species more appropriately compared to the other members from this genus because not every *Periplaneta* species is worldwide distributed. However, the specific name *americana* may be misleading that this cockroach species originated from America. Evidences show that it is of tropical Africa origin (Roth 1981).

Adult American cockroaches are 35–40 mm in length and shiny red to chocolate brown in color (Plate 2.1). They can be distinguished from the other two *Periplaneta* species found in Malaysia; *P. americana* has a pair of tapered and shorter cerci at the tip of abdomen compared to that of *Periplaneta brunnea* Bermeister and it lacks of yellow pale stripe presented on each edge of the front wing of *Periplaneta australasiae* (Fabricius) (Lee and Ng 2009). First five nymphal stages are of uniform pale brown in color while paler patches are developed on either edge of the dorso-median line of the pronotum during sixth nymphal stage (Cornwell 1968). Sexes of adult can be easily distinguished by the present of styli on the ninth abdominal segment only in adult male. Sexes can also be differentiated in nymphs by the presence of a sharp median notch on the caudal margin of the ninth sternum of the females whereas males have a smooth or a slightly indented end on their ninth sternum. In addition, wings of the adult males extend 4–8 mm beyond their abdomen while wings of the females are as long as their abdomen (Gould and Deay 1938).

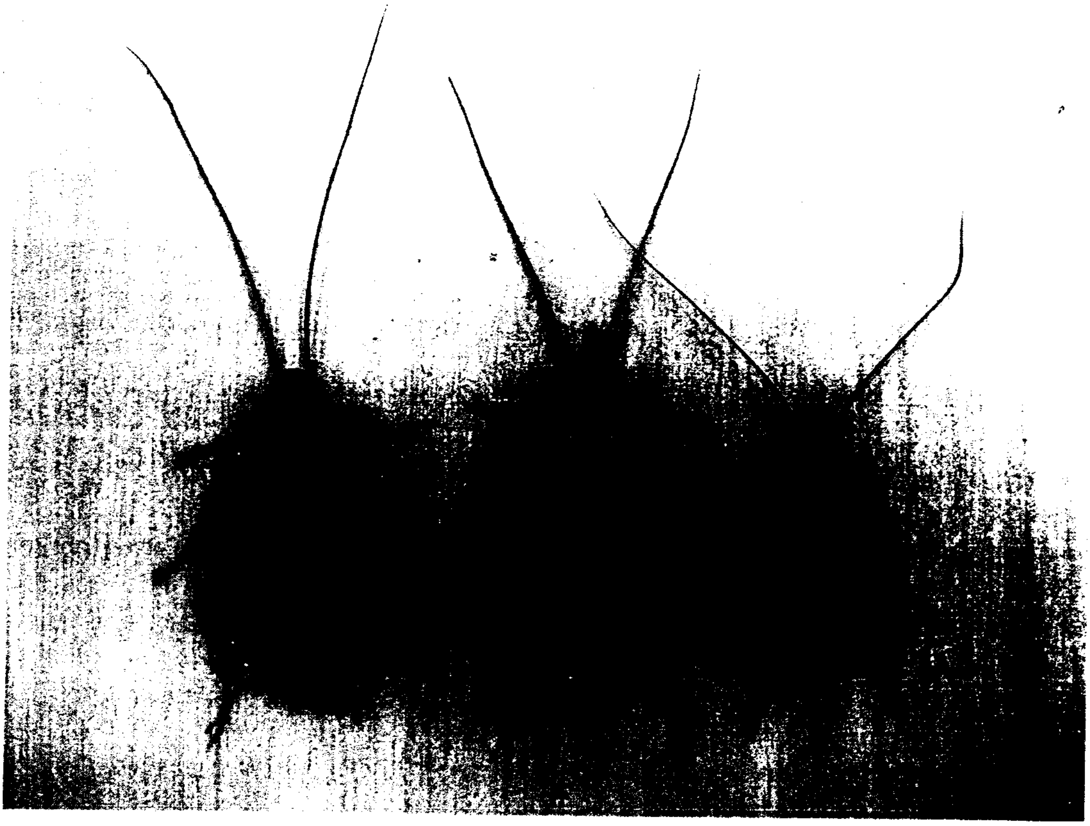

Plate 2.1. Dorsal view of *P. americana* male (left), female (middle) and nymph (right).

After a preoviposition period of 1–2 wk, a newly molted female *P. americana* begins to produce oothecae. Females produce 10–84 oothecae in their entire lifespan and are capable of depositing two oothecae per week during their peak reproductive period (Gould and Deay 1938, Roth and Willis 1956). Each ootheca contains 16 eggs arranged in two rows of eight eggs but the number of eggs that successfully hatch out is in the range of 11–14 eggs with a female to male sex ratio of 1.08:1 (Gould and Deay 1938, Roth and Willis 1956, Willis et al. 1958). Eggs enclosed in the hardened oothecal shell are provided with a protection from physical and moisture damage, water loss, and microbial invasions (Provine 1981). Ootheca with damaged keel suffers desiccation and this eventually leads to the death of the embryos contained inside (Roth and Willis 1955). Females normally chews out a hole on loose or soft substrate to deposit their ootheca and conceals the ootheca inside the hole with substrate particles held in place with their saliva (Rau 1943, Roth 1981, Gordon et al. 1994a, 1994b; Yeh 1995). In areas where loose and soft materials are not present, females may also attach its ootheca to the surface of substrate without concealment such as wall, cabinet and wood (Piper at al. 1978, Gordon et al. 1994a, 1994b). The incubation periods of oothecae range from 30 to 45 d (Lee and Ng 2009).

Nymphal development of *P. americana* varies from 5–15 mo but it normally lasts 4.5 mo. Number of molts for nymphs to mature into adults requires 6–14 molts (Cornwell 1968). Varying developmental time and number of molts are expected because life history studies of *P. americana* are conducted in different experimental conditions and geographical areas (Roth 1981, Cochran 1999). However, variations are also reported in constant controlled environment (Roth 1981). Even nymphs hatched from the same ootheca were reported to show great differences in number of molts and developmental time (Gould and Deay 1938). Nymphs living in group grow faster than those of isolated ones (Wharton et al. 1968). However, in natural population, *P. americana* tend to aggregate in their harborages during inactive periods due to attraction to aggregation pheromone secreted in their feces (Roth and Cohen 1973, Bell 1981).

The lifespan of adult *P. americana* ranges from 125 to 706 d in females and from 125 to 362 d in males (Rust 2008). One mating is sufficient for the females to produce oothecae in their lifespan (Cornwell 1968). Two sex pheromones, namely periplanone-A and periplanone-B, have been identified from female *P. americana* (Okada et al. 1990). It is hypothesized that periplanone-B is involved in long distance attraction of males to calling females whereas periplanone-A affects the behavior of the males within the vicinity of calling females (Seelinger 1985). Sex-specific vertical stratification is reported in *P. americana* in an outdoor environment around houses. Males were observed to perch higher than females during their active period at scotophase (Appel 1986). It is hypothesized that a thermal gradient facilitates upward movement of sex pheromones released by females reaching males located at higher levels (Schal 1982, Appel and Smith 2002). Males were observed to be attracted to calling females by flying up to a distance of 28 m (Seelinger 1984).

2.2 Economic and medical importance of cockroaches

Contamination of food, staining of clothes with fecal materials and saliva, soiling utensils with odor, and reduced aesthetic value of human living environment are examples of economic losses attributed directly from cockroach infestation (Cornwell 1976, Lee 2007). These damages rendered by cockroaches are difficult to estimate in monetary unit. However, expenses spent on cockroach management may give an estimate of the monetary costs incurred from cockroach problems (Brenner 1995).

In the United States, a total of 19,000 pest control companies made a total annual income of US$ 6.1 billion in 2004 and 22.4% of the total amount was contributed from services provided for cockroach control. It is estimated that services rendered for cockroach problems cost US$ 1 billion each year in the United States (Rust 2008). In Malaysia, 20% of the total income of pest management industry is also contributed from cockroach management (Lee 2007).

The associations of cockroaches with various pathogenic organisms have been reviewed in many literatures. Pathogenic bacteria, viruses, fungi, protozoans and helminthes are either isolated from field collected cockroaches or experimentally proved to be able to vector by cockroaches (Roth and Willis 1957, 1960; Roth 1981, Brenner 1995, Lee 1997, Lee and Ng 2009). In a recent survey on the bacteria fauna carried by *P. americana* in Singapore, a total of 59 bacterial species were isolated from *P. americana* collected from traps placed at manholes, bin chutes and floors (Lee and Ng 2009). Thirty-six species of these bacteria were pathogenic; 35 species were documented from cockroaches trapped in manholes while 23 species each was isolated from cockroaches collected from bin chutes and floor traps.

In addition, cockroaches are also known to produce allergens. To date, six and seven allergens have been identified in *B. germanica* and *P. americana*, respectively (Gore and Schal 2007). A study conducted in inner-city households showed that exposure to high level of cockroach allergen significantly contributed to an increase in hospitalizations and unscheduled medical visits, and a decrease in life quality among asthmatic children with cockroach allergy (Rosenstreich et al. 1997).

Inner-city Asthma Study Group reported that environmental intervention conducted to reduce indoor cockroach allergen level significantly correlates to a decrease in asthma-associated morbidity among asthmatic children with cockroach allergy (Morgan et al. 2004). In a recent study, Sever et al. (2007) showed that cockroach control alone, if implemented properly and thoroughly, can lead to a reduction in the level of household cockroach allergen. These studies demonstrate that both cockroach infestation and indoor cockroach allergens are important factors to be considered in treating household asthma.

2.3 Mark-recapture studies on pest cockroaches

2.3.1 American cockroach, *P. americana*

During the 1950s, several mark-recapture experiments were conducted to study the movement and dispersal of *P. americana* within and from sewers due to this cockroach species was reported to be a potential mechanical vector that may transfer disease organisms. To examine the possible dispersal of *P. americana* within and from sewers, Schoof and Siverly (1954) released 6500 radioactive-tagged *P. americana* into four manholes in a sewerage system and conducted trapping at surrounding manholes and premises for 8.5 wk at Phoenix, Arizona. Although a large number of *P. americana* was superimposed into the four manholes, only one radioactive-tagged *P. americana* was caught at a yard trap 18 m away from the release site and no radioactive-tagged cockroaches was found in the surrounding manhole traps. Eads et al. (1954) carried out another experiment to investigate the dispersal of *P. americana* from sewers in Tyler, Texas. Four releases of each 1000 enamel-painted cockroaches into their original manholes resulted in recaptures of two marked cockroaches in sewer manhole 352 m away and up to 28 marked cockroaches at adjacent apartments, houses and grocery shop. Subsequently, Jackson and Maier (1955, 1961) conducted two mark-recapture studies to examine the effects of population stress and seasonal factor on the dispersal of *P. americana* in sewers in Phoenix, Arizona. They found that induced population stress by superimposing 1200 radioactive-tagged cockroaches into a resident population of 300 cockroaches resulted in 5.9% (71 cockroaches) of the tagged cockroaches moving into surrounding house and yard traps up to 29 m away and up to 107 m in manhole traps. Meanwhile, the normal undisturbed population of 500 *P. americana* recorded only 0.8% (4 cockroaches) of tagged cockroaches moved into adjacent yard and manhole traps (Jackson and Maier 1955). In another set of mark-recapture studies, Jackson and Maier (1961) found similar results where 0.1–4.3% of the marked *P. americana* from both superimposed and undisturbed cockroach populations were recorded moving into adjacent apartments, yards and manholes in late spring while there was little or no movements when 300–1500 marked cockroaches were released into manholes in winter. They showed that dispersal of *P. americana* occurred in a normal condition and may increase to readjust to the carrying capacity of the environment such as sewer flooding and growth of the cockroach population.

Besides studies conducted on populations of *P. americana* in sewers, mark-recapture experiments were also conducted to study *P. americana* population in an outdoor environment and a green house (Appel 1986, Coler et al. 1987). Different from the marking techniques used in the previous studies on *P. americana* in sewers, Appel (1986) and Coler et al. (1987) marked cockroaches with an individual code that allowed assessment of the recapture rates, movement direction, sex-specific activity and estimation of population size and home-range. In a study of an outdoor population of *P. americana* in Houston, Appel (1986) reported a age-class structure of 73.2% adult females, 5.2% adult males, 19.6% large nymphs and 2.1% medium nymphs based on trap-catch. However, this age-class structure was inconsistent with the field observation that indicated approximately 70% nymphs and a 1:1 adult sex ratio. Laboratory experiment showed that the glass-jar traps were not biased toward trapping for any life stage. This suggests that stage-specific spatial distribution of *P. americana* in the field.

In a mark-recapture study conducted on a green house population of *P. americana*, Coler et al. (1987) found that cockroach movements were limited, where majority of the marked cockroaches were recaptured within 2 m of their release sites up to six weeks after release. Cockroach activity based on trap-catch and visual counting showed contrasting results. However, estimates of population density based on removal method, Jolly stochastic model and Fisher-Ford model indicated that jar-traps were more reliable at measuring the changes in cockroach density (Coler et al. 1987).

2.3.2 Smokybrown cockroach, *P. fuliginosa*

Smokybrown cockroaches, *P. fuliginosa*, are an important pest cockroach in southeastern United States, China and Japan (Appel et al. 1990). They are well-established at outdoors and frequently enter houses from outdoor reservoirs (Appel and Smith 2002). Using individually coded pieces of masking tape stuck on the tegmen, Fleet et al. (1978) reported that smokybrown cockroaches were most abundant from late summer (June) to early fall (July) in a 16-mo study conducted around a house in Texas. In addition to provide suggestion on optimum time to implement cockroach control, knowing the period of peak cockroach activity may also provide a reference for biological and behavioral study on outdoor smokybrown cockroach population because more observations can be made when cockroach population is large (Appel and Rust 1985, 1986; Brenner 1988, Brenner and Pierce 1991). In mark-recapture studies of *P. fuliginosa*, individual tagging techniques include adhesion of masking-tape pieces to tegmen and whole-body longitudinal marking with water-based paint pen (Fleet et al. 1978, Appel and Rust 1985, Brenner 1988, Brenner and Patterson 1988, Brenner and Pierce 1991). Recapture rates from those mark-recapture studies ranged from 9.9–52.3%.

Fleet et al. (1978), Brenner (1988) and Brenner and Pierce (1991) reported an age-class structure that consisted of 43–50% adult cockroaches while Appel and Rust (1985) found an age-class structure of 26% adult cockroaches. Type of bait, design and placement of traps were probably responsible for the differences in age-class structure of cockroaches caught in traps (Appel and Rust 1985, Brenner 1988). Fleet et al. (1978) and Appel and Rust (1985) reported 59% and 47% , respectively, of the marked cockroaches recaptured at traps other than their initial release sites. The mean distance traveled between successive recaptures was approximately 10 m for males and 6-10 m for females in their studies. Base on the mean distance traveled, they estimated a home range of 280–298 m^2 for males and 107–300 m^2 for females. Smokybrown cockroaches were not uniformly distributed in areas surrounding houses and were found to concentrate in various landscape features such as palms, trees with tree holes and woodpiles (Brenner 1988). Brenner and Pierce (1991) concluded from their mark-recapture study that smokybrown cockroaches were more mobile in the spring than were in the fall. Therefore, they suggest that invasion of smokybrown cockroaches into houses in the fall is probably a function between population size and distances of primary harborage sites to houses (Brenner and Pierce 1991).

In examination of the effects of meteorological factors on the activity of smokybrown cockroaches, Fleet et al. (1978) and Brenner (1988) found that the maximum and minimum daily temperatures correlated positively with cockroach trap catch whereas Appel and Rust (1985) reported there was no correlation between trap catch and maximum and minimum daily temperatures. It was proposed that low fluctuation in temperatures (< 4°C) in the 14-d study by Appel and Rust (1985) had little effect on trap catches compared to that of Fleet et al. (1978) conducted for a 16-mo period (Appel and Rust 1985, Brenner 1988). On the other hand, Brenner (1988) suggested that maximum daily temperature was more predictive of cockroach activity when temperatures were cool and remained above threshold of 10.5°C while cockroach activity was more predictive by minimum daily temperature during hot weather condition. Both Appel and Rust (1985) and Brenner (1988) found that rainfall affected trap catches of smokybrown cockroaches. Appel and Rust (1985) reported trap catches were lower when rains occurred in the late afternoon or evening compared to trap catches when rain occurred in the early morning or clear days. Meanwhile, Brenner (1988) found that trap catches were higher following raining days and were negatively proportional to the amount of rain.

2.3.3 Oriental cockroach, *B. orientalis*

Blatta orientalis (L.) is a pest cockroach found in temperate region. This cockroach species can be found both indoors and outdoors and is a major pest cockroach in the northern regions of United States and throughout Europe (Rust

2008). Distribution and movement of the oriental cockroach had been studied in and around apartment buildings in Virginia (Thoms and Robinson 1986, 1987). Porches of apartment buildings were identified as primary outdoor harborage sites whereas kitchens, bathrooms and living rooms were areas of indoor infestations (Thoms and Robinson 1986, 1987). Thoms and Robinson (1987) tagged adult oriental cockroaches trapped outdoor to investigate their movements into and around apartment buildings. In their studies, movement of oriental cockroaches outdoor was investigated by observing and trapping marked cockroaches at the 2-m grids defined within 4 m at the edges of apartment buildings. Of 483 re-sighted and recaptured marked cockroaches, 50% was found to stay close to one porch, 35% moved along one side of a building, 13% travelled between the front and back of a building, and 2% moved between buildings (Thoms and Robinson 1987). Another 2% of the recaptured marked cockroaches were found indoors in kitchens, bathrooms and living rooms and believed to enter houses via door thresholds and plumbing connections from their harborages at porches (Thoms and Robinson 1986, 1987). The mean distance moved by re-sighted and recaptured marked cockroaches was 8.4 m and 50 m was the longest distance moved (Thoms and Robinson 1987).

2.3.4 German cockroach, *B. germanica*

German cockroaches, *B. germanica,* are indoor pest cockroach with worldwide distribution. Their establishment indoor is depended on the availability of adequate food, water and shelter and warm and moist microhabitats. Therefore, they are commonly found in houses and restaurants and rarely found in outdoor environments (Cornwell 1968, Appel 1995). Several mark-recapture studies were conducted to study their distribution and movements within and between apartments. Owens and Bennett (1982), and Runstrom and Bennett (1984, 1990) concluded from their mark-recapture studies that intra- (within apartment) and inter-apartment (between adjoining apartments) movements of German cockroaches were detected and inter-apartment movement rates were higher in adjoining apartments with common plumbing connections compared to apartments without common plumbing connections. Owens and Bennett (1982) reported that intra- and inter-apartment movements of German cockroaches were not correlated with their population size. To evaluate the effect of repellent insecticide on the movement of German cockroaches, apartments were treated thoroughly with a sublethal concentration of pyrethrin insecticide in Owens and Bennett's study (1982). They found that this repellent insecticide increased inter-apartment movement while intra-apartment movement was reduced. However, Runstrom and Bennett (1984) reported contrasting results where both intra- and inter-apartment movements of German cockroaches were decreased in apartments treated with insecticides. This decrease in intra- and inter-apartment movement was suggested to be attributed to cockroach mortality due to the use of a lethal concentration of insecticide (Runstrom and Bennett 1984). Barcay et al. (1990) concluded from their mark-recapture studies that thorough application of insecticide did not affect German cockroach movement and distribution within apartments. They found that large nymphs were most mobile, followed by adults and small nymphs. This stage-specific movement patterns is in agreement with the findings reported by Rivault (1989). In a mark-recapture study of German cockroaches in a swimming-bath facility, Rivault (1989) interpreted from his findings that small nymphs were most aggregative and tended to explore farther as they molted into the older stages whereas adults tended to remain in the aggregation; nymphs require more foods and less crowded harborages as they grow while adult females need to hide when they bear ootheca and adult males remain in shelter to seek for a mate.

2.4 Biology of *A. hagenowii*

A. hagenowii is an endoparasitic wasp of cockroach oothecae (Plate 2.2). It has a wide range of hosts that includes *P. americana*, *P. brunnea*, *P. australasiae*, *P. fuliginosa*, *B. orientalis*, *Eurycotis floridana* (Walker), *Parcoblatta* spp., *Eurycotis biolleyi* Rehn and *Neostylopyga rhombifolia* (Stoll) but it shows preference for oothecae of *Periplaneta* sp. either in the field or laboratory experiments (Roth and Willis 1960, Piper et al. 1978, Hagenbuch et al. 1988, Lebeck 1991, Pawson and Gold 1993). Adult wasps are 1.8–2.0 mm in length with sizes varied according to the number of progeny developing in the ootheca (Cameron 1955). Adult females can live an average 2.8 d while males have a shorter average lifespan of 1.5 d. The lifespan of females and males can be extended to an average of 3.5–9.0 d and 1.8–5.0 d, respectively if they are fed with carbohydrate-based foods (Narasimham 1984). A female wasp commonly oviposits one to two times (range 1–5 times) in its entire lifespan with an average of 94 eggs (Roth and Willis 1954). Females that parasitize second ootheca have a larger egg supply than those females that oviposit only one ootheca (Heitmans et al. 1992). The females will allocate a smaller proportion of their eggs to the second ootheca as compared to the first ootheca which they have oviposited when these two oothecae are presented simultaneously. However, the

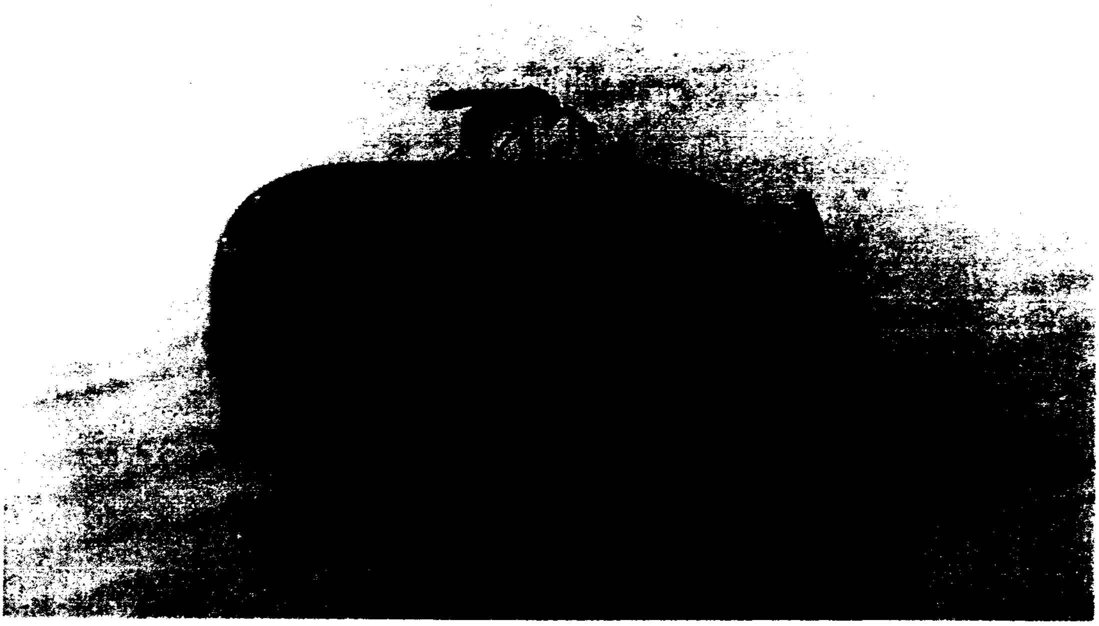

Plate 2.2. An *A. hagenowii* female probes an American cockroach ootheca with its tip of abdomen while other females examine ootheca with antennal tapping.

females allocate similar proportions of their eggs over two oothecae that it encounters one by one at different time (Heitmans et al. 1992).

The number of progeny produced from a parasitized ootheca is reported to range from 33 to 261 wasps (Lebeck 1991). Progenies emerging from a parasitized ootheca show a female to male sex ratio of 1:1 to 10.3:1 (Roth and Willis 1960, Suiter et al. 1998). The developmental time of the immature stages in ootheca ranges from 22 to 90 d (Roth and Willis 1960). However, the values of progeny number, sex ratio, and developmental time vary depending on the number of eggs developed in an ootheca (Roth and Willis 1954, Fleet and Frankie 1975, Narasimham 1984, Heitmans et al. 1992). For example, Narasimham (1984) showed that an ootheca subjected to parasitization by only one female *A. hagenowii* produced a more female-biased clutch of progeny (10:1 female: male sex ratio) compared to the one parasitized by two to five female wasps (3.12–6.94:1 female: male sex ratio). However, the mean progeny number of 88–100 wasps was greater and the mean developmental time of 33–38 d was shorter in ootheca parasitized by two to five females compared to the mean progeny number of 70 wasps and mean developmental time of 45 d recorded from ootheca parasitized by only a female. Parthenogenetic reproduction also exists in *A. hagenowii* where unmated females produce only male progenies (Roth and Willis 1954, Edmunds 1955).

2.5 Effects of killed oothecae of *P. americana* on parasitism and development of *A. hagenowii*

Accidental release of pests from unparasitized hosts into the field during biological control program can be prevented by using killed hosts (Suiter et al. 1998).

The use of killed hosts also eliminates the need to handle individuals emerging or hatching from unparasitized hosts in rearing cages (Geden and Kaufman 2007). In addition, hosts can be killed at a stage favorable for parasitoid production and these high quality killed-hosts can then be stockpiling for future use in mass-production or field release (Chen and Leopold 2007). Exposure of hosts to high and low temperatures, ultraviolet (UV) radiation and irradiation are common techniques employed to kill hosts. These host-killing techniques also have been used in the evaluation of suitability of killed oothecae of *P. americana* as hosts for *A. hagenowii* and *Evania appendigaster* (L.), another oothecal parasitoid of *P. americana* (Suiter et al. 1998, Hwang and Chen 2004, Bressan-Nascimento et al. 2008).

Suiter et al. (1998) and Hwang and Chen (2004) evaluated the suitability of freeze-killed oothecae of *P. americana* as hosts for parasitism and development by *A. hagenowii* and *E. appendigaster*, respectively. They reported that exposure of oothecae to freezing at −16°C for 6–36 h was able to terminate embryonic development of *P. americana*. However, Suiter et al. (1998) found that 50% of the oothecae killed at 24-h freezing (−16°C) did not able to produce *A. hagenowii*. Hwang and Chen (2004) reported similar finding where oothecae exposed to −16°C for 6–36 h were not suitable for development of *E. appendigaster*.

The use of heat in killing oothecae of American cockroaches was tested in Hwang and Chen's study (2004). Heating of oothecae at 50°C for 6–36 h terminated the embryogenesis of *P. americana*. Nevertheless, Hwang and Chen (2004) found that longer periods of heating may deteriorate the quality of oothecae as hosts for *E. appendigaster*. Therefore, they suggest that heating oothecae for 6 h is a viable alternative for killing *P. americana* oothecae.

Exposure of American cockroach oothecae to irradiation as a mean to kill the hosts was attempted in the studies conducted by Suiter et al. (1998) and Hwang and Chen (2004). They reported that oothecae subjected to irradiation did not change their suitability as hosts as those of the live one for development by *A. hagenowii* and *E. appendigater*, respectively.

In addition to freezing, Bressan-Nascimento et al. (2008) reported that *P. americana* oothecae that were subjected to chilling at 0–5°C for 5 d was sufficient to terminate their embryonic development. Parasitism, emergence rates and developmental time of *E. appendigaster* and *A. hagenowii* in those chill-killed oothecae were not significantly different to that of the live ones.

Although UV radiation was reported as a viable host-killing method in other insect hosts (Hu et al. 1999, Moreno et al. 2009), Hwang and Chen (2004) showed that exposure of *P. americana* oothecae to UV radiation (254 nm) for 10–150 min was unable to terminate their embryonic development. They suggested that oothecal shell of *P. americana* may not allow penetration by UV radiation.

2.6 Evaluation of the biological control potential of *A. hagenowii*

Many authors suggest that *A. hagenowii* is a promising biological control agent of cockroaches. This is probably due in part to their prevalence in natural cockroach populations (Cameron 1955, Roth and Willis 1960, Lebeck 1991). Oothecae collected from the fields (United States, India, Saudi Arabia and Japan) reported a parasitism range of 16–48% in *P. americana*, 22–84% in *P. fuliginosa* and at 12.5% in *B. orientalis* (Cameron 1955, Fleet and Frankie 1975, Kanayama et al.

1976, Piper et al. 1978, Narasimham and Sankaran 1979). Attempts to evaluate the potential of *A. hagenowii* in controlling blattid cockroaches had been conducted in simulated-rooms and field experiments (Roth and Willis 1954, Piper and Frankie 1978, Hagenbuch et al. 1989, Pawson and Gold 1993, Suiter et al. 1998). The performances (parasitism rate) of *A. hagenwoii* in most of the evaluations were measured by placing laboratory-obtained oothecae (sentinel oothecae) because natural deposited oothecae are difficult to locate and obtain.

Roth and Willis (1954) evaluated the biological control potential of *A. hagenwoii* in a laboratory and a basement. Oothecae of *P. americana* were distributed in crevices and on shelves, ranging from floor level to areas near ceiling. A release of 450, 800 and 1000 female wasps, which equals to 5.1, 7.9 and 10.4 female wasps per distributed ootheca, resulted in a parasitism rate of 28, 74 and 83% on sentinel oothecae distributed in those rooms. The highest parasitism rate was achieved in releases with 7.9 and 10.4 female wasps per ootheca ratio which indicated that these two ratios were suitable to achieve control against American cockroaches. Oothecae located in all parts of the room were found to be located and parasitized by *A.* hagenowii; suggesting that the searching efficacy of *A. hagenwoii* was satisfactory in enclosed room condition.

In another study, Hagenbuch et al. (1989) tested inundative releases of *A. hagenwoii* in rooms (2.4 by 2.4 by 2.8 m high) artificially infested with *P. americana*. Releases of 200 mixed-sex wasps (50% female) three times a week were made for the first 6 wk and monitoring on parasitism rate of the oothecae found inside the rooms were conducted weekly in their 17-wk evaluation. A parasitism range of 95–98% was reported on oothecae collected from the rooms in their 17-wk study. *A.*

hagenowii were established inside the rooms after releases were terminated and subsequent generations of *A. hagenowii* also were found to maintain a high parasitism rate on oothecae laid after the termination of releases. Base on the number of oothecae deposited in the rooms and the number of female wasps produced per parasitized ootheca, a release ratio of 8.3 female wasps per ootheca was estimated. In an evaluation of the parasitism rate of oothecae deposited on various locations within the rooms, oothecae deposited on the floor, inside cabinet and in food dishes recorded a parasitism range of 93–100% whereas only 50% parasitism was found on oothecae attached close to ceilings. This indicates that height may be a factor affecting host searching ability of *A. hagenowii*. In addition, Hagenbuch et al. (1989) also tested synergism effect by incorporating a hydramethylnon bait station in some of the release chambers from week 12–17. They found that *A. hagenowii* were still able to maintain a high parasitism rate of ca. 96% on the deposited oothecae; indicating that hydramethylnon did not have adverse effect on *A. hagenowii*. In another experiment, Bell et al. (1998) also found that (S)-hydroprene, a juvenile hormone analogue, did not affect the ability of *A. hagenowii* in parasitizing oriental cockroach oothecae.

Evaluations of *A. hagenowii* in outdoor environments also showed some promising results. Pawson and Gold (1993) evaluated biological control potential of *A. hagnowii* in plumbing chases infested with *P. americana* and compared its efficacy with different release strategies. Release of 300 female wasps from parasitized oothecae once a week and twice a week, and release of 50 free-living females once a week resulted in overall parasitism rate of 30.6, 18.2 and 20.6% on sentinel oothecae placed in the chases over a 6-wk study. Weekly releases of 300 *A. hagenowii* in parasitized oothecae and 50 free-living females recorded a parasitism range of 23–39% and 13–35%, respectively, whereas bi-weekly releases of 300 female *A. hagenowii* in parasitized oothecae showed variation in parasitism rates that ranged from 0–44%. Sentinel oothecae distributed within 0.5–5.0 m from the release site recorded 21–35% parasitism rate while only 9% was recorded for sentinel oothecae located 16 m away from the release site. In comparison to the studies by Roth and Willis (1954) and Hagenbuch et al. (1989), Pawson and Gold (1993) suggest that lower parasitism rates obtained in their study were probably due to lower number of *A. hagenowii* released and a larger space of the chases in their studies. However, it is encouraging that noticeable rates of parasitism (13–35%) are recorded with only 50 free-living female *A. hagenowii* released weekly.

In outdoor treehole microhabitat infested by blattid cockroaches weekly releases of ca. 650 female *A. hagenowii* resulted in a parasitism range of 50–100% on sentinel *P. americana* oothecae, which was significantly higher than that of non-release sites with a parasitism range of 10–40% on sentinel oothecae in a 30-wk study (Suiter et al. 1998). Suiter et al. (1998) found that parasitism rates of sentinel oothecae in the release site remained higher than that of non-release site over a 10-wk period after releases were terminated suggesting that *A. hagenowii* were established in oothecae deposited naturally in the field.

In an attempt to evaluate the potential of using *A. hagenowii* in controlling *P. americana* population in sewers, Reierson et al. (2005) made two releases of 30 oothecae parasitized by *A. hagenowii* into manholes of sewerage systems. Although the number of cockroaches were not reduced over an 18-wk monitoring period after releases, Reierson et al. (2005) found that the emergence of parasitized oothecae in the two releases were not in consistent to those parasitized oothecae which were allowed to emerge in the laboratory. They suggest that the environmental conditions in the sewer may affect *A. hagenowii* activities.