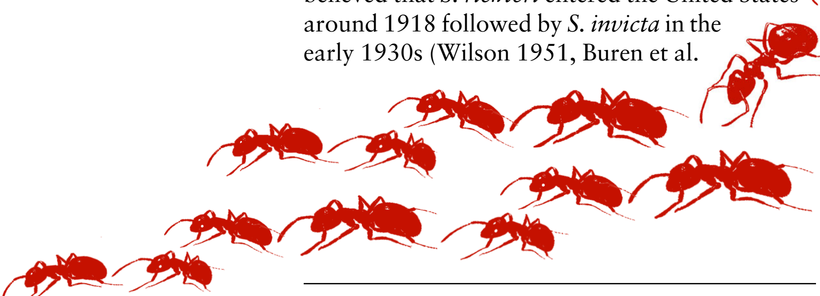
(Hymenoptera: Formicidae): An Historical Perspective of Treatment Programs and the Development of Chemical Baits for Control

The invasion of the red imported fire ant in the United States and its impact on wildlife, humans, and agriculture due to its high reproductive capacity, aggressive foraging behavior, and lack of effective natural enemies.

David F. Williams, Homer L. Collins,[1] and David H. Oi

The major ant pest in the southern United States in the early 1900s was the Argentine ant *Linepithema humile* (Mayr) (Wojcik 1994). Thus, there was little concern when imported fire ants were detected in and around Mobile, AL, by Loding (1929). In a short time, this level of concern changed as this new, more serious pest became a major problem. At the time of its discovery, this new pest was believed to be only one species, *Solenopsis saevissima* (variety *richteri* Forel), but with two color forms (Wilson 1951, 1953; Wilson and Brown 1958). It was not until 1972 that Buren's taxonomic revision assigned the currently used scientific names: *S. richteri* Forel, the black imported fire ant; and *S. invicta* Buren, the red imported fire ant. It is believed that *S. richteri* entered the United States around 1918 followed by *S. invicta* in the early 1930s (Wilson 1951, Buren et al. 1974). To complicate the problem, these two species have interbred to form a hybrid (Wilson 1953, Vander Meer et al. 1985a), which is located in the northern areas of Mississippi, Alabama, Georgia, and southern Tennessee. However, *S. invicta* is most widespread, presents the greatest problem, and is the target of most of the research and control programs.



Since its introduction into the United States over 60 years ago, *S. invicta* has spread to more than 316 million acres (128 million hectares) in several states and Puerto Rico (Callcott and Collins 1996) and recently has reached New Mexico, Arizona, and California (Code of Federal Regulations, 2000) (Fig. 1). It spread from Mobile naturally by mating flights and floating colonies on water during floods and artificially by humans through shipment of infested nursery stock and sod (Lofgren 1986a). This spread has been aided by the development of a multiple queen (polygyne) form. Because of the numerous queens, it is easy to transport small colonies (queen, brood, and workers) (Fig. 2) with soil and nursery stock. The recent invasion of New Mexico, Arizona, and, especially, California could be the springboard *S. invicta* needs to spread along the west coast of the United States. Isolated infestations found in Kentucky, Virginia, Maryland, Washington, DC, and Delaware were eliminated by State Plant Health Regulatory Officials (R. Milberg, personal communication), but this pest probably will continue to reinfest these areas and eventually become established in some

[1]U.S. Department of Agriculture, Animal Plant Health and Inspection Service, Plant Protection and Quarantine, Gulfport Plant Protection Station, 3505 25th Avenue, Building 16, Gulfport, MS 39501 and U.S. Department of Agriculture, Agricultural Research Service, Center for Medical, Agricultural, and Veterinary Entomology, P.O. Box 14565, Gainesville, FL 32604.

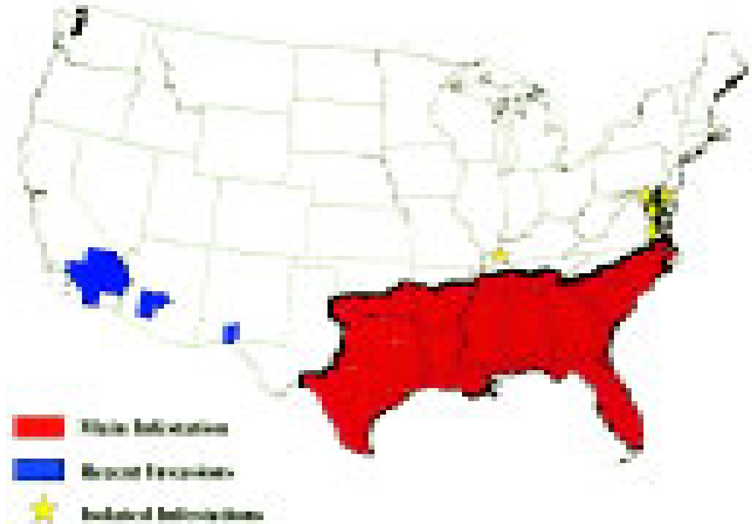


Fig. 1. Distribution map of *Solenopsis invicta* in the United States showing the main infestation (red), recent invasions (blue), and isolated infestations (yellow star) that are reported to have been eradicated.

of them. The current *S. invicta*/*S. richteri* quarantine map is maintained by the United States Department of Agriculture (USDA)-Animal Plant Health Inspection Service (APHIS)-Plant Protection and Quarantine (PPQ) (http://www.aphis.usda.gov/oa/antmap).

Solenopsis invicta has had a substantial impact on wildlife, humans, and agriculture (Adams and Lofgren 1981, Adams 1986, Tedders et al. 1989, Allen et al. 1994, Barr et al. 1994, Barr and Drees 1996). It often is the dominant species in the areas it infests because of its high reproductive capacity, aggressive foraging behavior, and lack of effective natural enemies. It can cause an overall reduction in the biological diversity of the areas it infests (Porter and Savignano 1990, Porter et al. 1991, Vinson 1994). Not surprisingly, the most noticeable problem is stinging of humans that, in some cases, has caused serious injuries (Fig. 3) and even death to hypersensitive individuals from anaphylactic shock. This has been reported in individuals having less than 150 stings to just a single sting (Vetter and Visscher 1998). Anaphylaxis occurs in 0.6% to 6% of the individuals who are stung, and more than 80 deaths have been caused by anaphylatic reactions to fire ant stings (deShazo et al. 1990, 1999; deShazo and Williams 1995). In addition, more than 50% of the people living in fire ant areas are stung annually (deShazo et al. 1999). This ant is a definite public health concern (Fig. 4) and the problem is becoming worse with the expansion of its territory (Kemp et al. 2000).

In addition to medical concerns, the impact of *S. invicta* on domestic animals also is a major problem (Fig. 5). In a survey of veterinarians conducted in Texas, more than 80% cited this ant as a threat to livestock health and as causing economic loss. Cattle accounted for over 50% of the animal deaths reported (Barr et al. 1994).

Solenopsis invicta is also responsible for damage to such agricultural commodities as soybeans, citrus, potatoes, corn, okra, and eggplants (Lofgren and Adams 1981, Adams 1986, Lofgren 1986b). Additional costs are imposed on the nursery and sod production industries because of federal quarantine that prohibits the movement of untreated nursery stock, sod, and other regulated articles into areas not infested by fire ants (USDA-APHIS-PPQ 1999, Code of Federal Regulations 2000). Thus, all shipments of plant materials must be treated with approved insecticides before movement out of the quarantined areas. Although the exact economic costs of fire ant damage and control are unknown, estimates have been from more than a half billion to over a billion dollars per year (Thompson et al. 1995, Thompson and Jones 1996, U.S. Senate Bill S.932 1997).

The control of *S. invicta* has taken many twists and turns during the years since its first discovery with a great deal of advice given, numerous solutions recommended, and many control techniques

Fig. 2. Small colony of *Solenopsis invicta* with queen surrounded by workers and immature stages. These colonies can be transported easily with soil and nursery stock.

Fig. 3. Photographs of multiple *Solenopsis invicta* stings. The *USA Today* newspaper article (21 September 1999) reported on nursing-home deaths caused by fire ants.

tried. However, it is still with us and its range expansion continues to pose major problems. During the 60+ years since the first report of this ant, millions of dollars have been spent by federal and state governments in attempts to control or eradicate it. It is without a doubt, one of the most studied ants in the world as well as the most expensive, considering the total amount of money that has been spent on control programs and research on its biology and ecology. In 1997, the Texas legislature appropriated 2.5 million dollars for fire ant research, control, and extension (Drees 1998); and the state of California has proposed funding of 8.7 million dollars in fiscal year 1999/2000 and 7.3 million dollars annually for the subsequent 4 years to eradicate/control this pest (California Department of Food and Agriculture, Report to the Legislature, June 2000). Funding for research on this ant has been cyclic with periods of highs and lows. Funding varies according to demands by the public on government agencies to control or eradicate *S. invicta,* media coverage on the amount of damage and even deaths resulting from this ant, and outcry expressed by the public when it moves into new areas. In this paper, we review the history of treatment programs and the development of baits for control, and offer some thoughts on its management for the future.

Fig. 4. *Solenopsis invicta* mounds next to gravestone (Saucier, MS). This is not an uncommon sight in cemeteries in infested areas.

When imported fire ants were first collected in 1929, their range was limited to the northern Mobile area and the nearby town of Spring Hill (Lofgren 1986b). Within 2 years, they were noticed in other small communities and had spread to an adjacent county. Six years later, their populations had increased sufficiently to cause local people to demand action by government agencies. Thus, the first organized control program began in February 1937 in Baldwin County, AL, under the cooperative efforts of federal, state, and county agencies. The control method consisted of opening a mound with a shovel, applying 1-3 oz (28-84 g) of 48% calcium cyanide dust, and then covering up the opening with soil. Approximately 2,000 acres (800 ha) of cropland were treated with more than 80% control reported (Eden and Arant 1949).

With the beginning of World War II, organized control programs for *S. invicta* were temporarily halted. Soon thereafter, surveys revealed that the ant had spread not only into neighboring counties in Alabama, but into the states of Mississippi and Florida. Isolated infestations were also found in Alabama and Mississippi over 150 km away from the main population (Wilson and Eads 1949). In 1949, Wilson and Eads made the first study of this ant's taxonomy, distribution, biology, and economic importance. They reported that individual queens or colonies could be transported over long distances via rail car and by floating on floodwaters. Although the above still are important means of dispersal, the shipment of infested nursery stock was, in all probability, the major means of its rapid range expansion (Culpepper 1953). Even today, the movement of infested nursery stock, sod, and bee hives is one of the principal methods by which uninfested areas, such as California, that are far removed from the major infestation, become infested with *S. invicta.*

In 1948, control operations began anew with $15,000 being appropriated by the state of Mississippi for *S. invicta* treatments with chlordane dust. The Alabama State Department of Conservation provided chlordane to farmers in southern Alabama (Wilson and Eads 1949) (Fig. 6). In addition, the Louisiana legislature funded the purchase of chlordane for farmers at cost, and the Louisiana Extension Service conducted demonstrations on how farmers should apply the insecticide. The Arkansas Plant Board conducted an eradication project in 1957 on 12,000 acres in Union County, and the city of El Dorado applied granu-

Fig. 5. Pastures infested with numerous *Solenopsis invicta* mounds in Lakeland, FL (left), and Opelousas, LA (right). Imported fire ants can be a threat to livestock and cause economic losses in the cattle industry.

lar heptachlor by aircraft at a rate of 2 lb/acre (2.24 kg/ha) with excellent results (USDA-ARS 1958).

Research on *S. invicta* began slowly with an imported fire ant research program (1949-1953) at the USDA facility at Spring Hill, AL. In addition, research efforts were initiated on biology and control of this ant at Auburn University in Alabama and Mississippi State University in 1948-1949. An extensive 4-year survey by the USDA in 1953 showed that the ant had spread to 102 counties in 10 states (Culpepper 1953). Shortly thereafter, mounting public complaints and pressure forced state and federal legislators to act. The Southern Association of Commissioners of Agriculture petitioned the U. S. Congress in 1957 to provide funding to the USDA to begin a federal-state cooperative control and eradication program as soon as possible (Lofgren 1986a). The U. S. Congress appropriated $2.4 million on 28 August 1957 for the project (Canter 1981). Two months later, the Plant Pest Control Division, Agricultural Research Service, USDA, and the Southern Plant Board developed guidelines for the program. The eradication program dictated the use of aerial and ground applications of granular heptachlor or dieldrin (USDA-ARS 1958, Lofgren et al. 1975) (Fig. 7). The first treatments were applied in November 1957, at a rate of 2 lb active ingredient (AI) per acre (2.24 kg/ha). With the initiation of the control program, the USDA realized that a Methods and Development Laboratory was needed to improve control methods. The laboratory was established at Gulfport, MS, in October 1957 to meet two goals: (1) reduce the amounts of heptachlor and dieldrin needed for control and (2) develop a toxic bait for control (Lofgren 1986b). In addition to the application of insecticides, on 6 May 1958, a quarantine was promulgated requiring that all shipments of nursery plants, grass sod, sand, gravel, and wood products with attached soil be treated with an approved insecticide (Fig. 8) before the product could be shipped out of an infested area (Anonymous 1958). Soon after the first treatments with heptachlor, some mortality of nontarget wildlife was noted (George 1958). Research by the USDA determined that lower insecticidal rates were effective. Consequently, in 1959, the rate of heptachlor was reduced to 1.25 lb (AI)/acre (1.4 kg/ha) and in early 1960, the rate was reduced again to 0.25 lb (AI)/acre (0.28 kg/ha) with two applications 3 and 6 months apart (Lofgren et al. 1961, 1965). The growing concern about detrimental effects on wildlife resulted in intense criticism by many conservationists (Brown 1961), and Senator John J. Sparkman and Congressman Frank W. Boykin of Alabama lobbied for suspension of the fire ant eradication/control campaign. Finally, with the discovery of heptachlor epoxide residues in meat and milk, and the Food and Drug Administration's reduction of residue tolerances for heptachlor in harvested crops to zero (Canter 1981), the fire ant control program for all practical purposes was over.

Scientists conducting research on *S. invicta* were aware of the potential problems with large-scale programs using heptachlor and dieldrin, so concurrent research was conducted during the early 1960s to develop baits for control of *S. invicta* at the USDA and at Auburn and Mississippi State Universities. It was believed that baits would be more environmentally acceptable than residual contact insecticides because they would use a relatively small amount of active ingredient in the formula-

Fig. 6. George H. Culpepper, USDA, showing Alabama farmers how to treat a *Solenopsis invicta* mound with chlordane drench. USDA photograph taken in 1952.

Fig. 7. Heptachlor and dieldrin insecticides were used by federal and state governments and by individuals in the 1950s in an effort to combat *Solenopsis invicta.* An eradication program initiated in 1957 dictated the use of aerial and ground applications of granular heptachlor and dieldrin.

tion. However, the requirements for an effective toxicant in fire ant bait are strict, and researchers faced several challenges in the development of baits. For example, the toxicant in the bait must (1) exhibit delayed toxicity so that it can be distributed to most members of the colony before the ants die, (2) be effective over a wide dosage range (preferably a 10- to 100-fold range) so that dilution of the toxicant is not a factor when transferred among members of the colony via trophallaxis, (3) not be repellent, and (4) be easy to formulate with foods and carriers (Stringer et al. 1964, Williams 1983, Banks et al. 1985). Few chemicals have been successful as bait toxicants for this species because of these restrictions. Those that met the requirements were formulated as follows: a toxicant (the active ingredient usually less then 1.0%), an attractant such as soybean oil, and an inert carrier. Travis (1939) conducted field studies with baits containing thallium sulfate or thallium acetate in syrup against the fire ant *Solenopsis geminata* (F.). Thallium acetate showed some promise in field studies. Green (1952) reported that a bait consisting of thallium sulfate, corn meal, and corn oil showed promise against *S. invicta* colonies in the laboratory but was ineffective in the field. Hays and Arant (1960) reported that a peanut butter bait containing low concentrations (0.125% [AI]) of Kepone (decachlorooctoahydro-1,3,4-metheno-2H-cyclobuta[ed]pentalen-2-one) and placed in soda straws gave 100% control. Other bait formulations containing Kepone also showed effectiveness, giving more than 90% control (Lofgren et al. 1961). However, because peanut butter bait was not practical for large scale treatments, scientists at the USDA, Methods and Development Laboratory in Gulfport, MS, began a search for an effective carrier for oil baits as a treatment in the eradication program (Lofgren et al. 1963). Aside from the effectiveness of the active ingredients killing *S. invicta,* the bait must (1) be composed of readily available low-cost materials; (2) be easily formulated; (3) be easy to apply with conventional application equipment; (4) not be affected by normal rainfall immediately following application; (5) not be a hazard to human, domestic animals, wildlife, and aquatic organisms; and (6) not accumulate in milk, meat of grass-foraging animals, or on vegetables. Following the evaluation of numerous materials, Lofgren et al. (1963) discovered that a corncob grit granular material met the above requirements. At the same time, they began testing a new active ingredient, mirex (dodecachlorooctahydro-1,3,4-metheno-2H-cyclobuta (cd) pentalene). The preliminary results with this compound were promising (Lofgren et al. 1962). Thus, emphasis was shifted from Kepone to mirex because it was less toxic to mammals, not as repellent to ants, and gave better control (Lofgren et al. 1963). Several rates and formulations of mirex were tested during 1961 and 1962. In 1963, the application rate was standardized at 2.5 lb per acre (2.8 kg/ha = 8.4 g [AI]/ha) and 2 years later was reduced by one-half to 1.25 lb per acre (1.4 kg/ha = 4.2 g [AI]/ha) (Lofgren et al. 1964). Thus, the new bait formulation for large scale treatments of *S. invicta* consisted of the toxicant mirex (0.075%) dissolved in soybean oil (14.925%) and impregnated on corn cob grits (85%), which provided 99 to 100% control in numerous trials (Lofgren et al. 1961,1962, 1963, 1964; Stringer et al. 1964). In field tests on 63 plots of 1 acre each (0.4 ha), an average of 98% control was obtained; on large area treatments with aircraft on approximately 640,000 to 1,000,000 acres (259,000 to 405,000 ha), an average of 96% control was obtained (Lofgren et al. 1963, 1964; Stringer et al. 1964; Banks et al. 1971, 1972, 1973a, 1973b). In 1962, because of the low application rate and the apparent lack of harm to the environment, mirex bait became the standard treatment for *S. invicta* control, thus replacing heptachlor (Lofgren et al. 1975). This new method of treatment replaced extremely long residual chemicals (heptachlor, dieldrin, aldrin, and chlordane) with a toxicant in a bait formulation that had little residual activity. However, because the bait lacked residual activity,

Fig. 8. Applying insecticides to nursery stock before shipment required by federal quarantine in Folsom, LA (left and upper right), and Long Beach, MS (lower right).

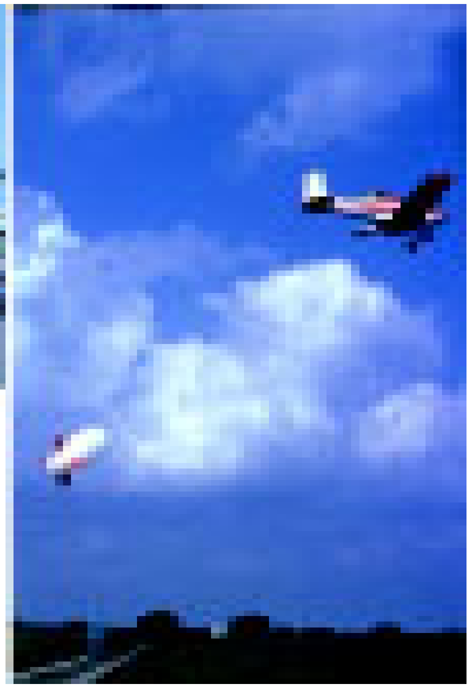


Fig. 9. Converted WWII bomber aircraft (left) were widely used to apply mirex bait, 1962-1978. Present-day single engine aircraft (right) applying imported fire ant baits. The balloon with red fins was used to mark the treatment area.

it allowed *S. invicta* to quickly reinfest treated areas and, thus, required repeated applications. The most extensively used bait formulation was 0.3% mirex, 14.7% soybean oil, and 85% corncob grits (Banks et al. 1976). Application of the bait was made with ground and aerial equipment. Mirex bait was applied to more than 140 million acres (56 million ha) from 1962 to 1978 (Lofgren et al. 1975, Williams 1983) (Fig. 9). However, because many treatments consisted of three applications to the same area, the total area actually receiving mirex bait in the United States was about one-third of the above or approximately 46.6 million acres (18.6 million ha) (Lofgren 1986a). The effectiveness of mirex and low cost of application led Lofgren and Weidhaas (1972) to suggest that mirex bait could be used to eradicate *S. invicta* over a 2-million acre area using a total of three to nine applications, provided the levels of control were 90 to 99.99%. Although federal funding for the fire ant program decreased from 1964 to1966, the continuing problems caused by this pest resulted in pressure from the Southern Plant Board for the USDA and Congress to propose an eradication effort using mirex bait. Because no research had been done on this, the Senate Agriculture Appropriations Subcommittee requested a study on the feasibility of an eradication effort. The Insects Affecting Man and Animals Research Laboratory (USDA-ARS) in Gainesville, FL, received funds in 1967 to begin tests to determine if the use of mirex bait could eradicate *S. invicta* from large areas (Lofgren et al. 1975). Three study sites were established in the areas of (1) Savannah, GA (approximately 2,131,244 acres or 850,000 ha), (2) Tampa-St. Petersburg, FL (approximately 626,808 acres or 250,000 ha), and (3) Columbus-Starkville, MS (approximately 256,000 acres or 102,000 ha). Control of this ant was excellent with 98 to 100% mortality of colonies in all treatments. However, even with this high rate of control over large areas, reinfestation still occurred, and Banks et al. (1973b) indicated that their results did not prove conclusively that mirex baits could be used to eradicate the *S. invicta*.

Although there still were discussions about using mirex bait for eradication of *S. invicta,* it would not be pursued because during the late 1960s to mid-1970s, scientists from the USDA and other institutions discovered that mirex residues not only persisted in the environment but accumulated in nontarget organisms and were toxic to estuarine organisms (Butler 1969; Lowe et al. 1970, 1971; Markin et al. 1974a, 1974b; Spence and Markin 1974; Bookhout and Costlow 1976). These studies revealed the detrimental aspects of mirex and raised concerns of environmental damage. Court injunctions to stop its use were initiated in 1970 but were temporarily denied. However, the U.S. Department of the Interior banned all use of mirex on public lands under its management in 1970 (Canter 1981), and the U. S. Environmental Protection Agency (EPA) issued a notice of cancellation of registration of mirex in 1971. During the issuance, severe restrictions were placed on the use of mirex (Ruckelshaus 1972). Finally, it was reported that mirex was a potential carcinogen (Ulland et al. 1977), and, after several years of hearings, all registrations of mirex were canceled by the EPA effective 31 December 1977 with the use of existing stocks to end 30 June 1978 (Johnson 1976). Excellent reviews of the federal-state fire ant control program with mirex are given by Alley (1973) and Lofgren (1986a). Although the use of mirex definitely was over, the Mississippi Authority for Control of Fire Ants (MACFA), a division of the Mississippi Department of Agriculture and Commerce funded research efforts in the mid-

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to late 1970s to develop a biodegradable formulation of mirex. The resulting formulation, known as ferriamicide, contained mirex, degradation enhancers, antioxidants, and kepone inhibitors (Alley 1982). An Experimental Use Permit to evaluate ferriamicide was granted by EPA on 9 September 1977. Collins (1979) reported 84% control with ferriamicide bait 12 weeks following aerial application. In 1981, MACFA submitted a request for conditional registration of ferriamicide. However, this request subsequently was denied by the EPA, and the bait never was commercialized.

The cancellation of mirex left the public without any chemicals registered as baits for the control of *S. invicta.* The only products available were those used for treating individual fire ant mounds, and they were not practical or economical for treating large areas. Southern constituents put pressure on Congress, which resulted in intensified efforts by the USDA to find replacement chemicals for use in baits for fire ant control. The difficulty in finding a replacement for mirex can be appreciated when we consider the 40-year period from 1958 to 1998. During this time, over 7,200 chemicals were evaluated by the USDA for use in baits against fire ants and only nine became or will become available commercially. Two of these, mirex and ProDrone are no longer available.

The environmental concerns with using mirex led the USDA to begin an accelerated screening program in the mid-1970s for a replacement toxicant for fire ant baits. Hundreds of compounds were evaluated. In 1976, a new class of compounds, the amidinohydrazones, were received from American Cyanamid Company, (Princeton, NJ) for evaluation against cockroaches and imported fire ants. Several of these compounds appeared promising in laboratory tests as baits against *S. invicta.* However, the most promising, AC 217,300 (hydramethylnon), was disappointing in field tests. It later was determined that the problem was low solubility of the hydramethylnon in the soybean oil attractant. Testing of over 100 cosolvents revealed that the addition of oleic or linoleic acid greatly increased the solubility (Banks et al. 1985). With increased solubility, the chemical exhibited excellent results in laboratory tests (Williams et al. 1980) and small and large field trials (Banks et al. 1981, Harlan et al. 1981). Williams et al. (1980) found that although AC 217,300 killed the colony queen, it did not kill all of the workers in large colonies. Because of this, a new field technique was developed to evaluate effects other than complete colony kill. This evaluation method (Harlan et al. 1981, Lofgren and Williams 1982) is based on the estimated number of worker ants in a colony plus the presence or absence of worker brood to determine a population index. The absence of a worker brood indicates that the colony does not contain a normally functioning queen. The present population index method is a standardized weighting system for colonies of *S. invicta* and has been used by the USDA and other fire ant researchers since 1982.

Additional field trials with AC 217,300 were conducted in the spring and fall of 1978, using 1.7-49.78 g (AI)/acre with ground equipment on pastures; and in the spring of 1979, using 2.3-7.9 g (AI)/acre with aircraft on roadsides and noncropland. These tests involved several types of carriers such as corn cob grits, puffed corn, pregelled defatted corn grits, and pregelled degermed corn grits (Fig. 10). Pregelled defatted corn grits were selected for the remaining field evaluations (see below) because they absorbed more oil and were readily available. However, because pregelled defatted corn grits formulated with 30% soybean oil caused problems with the delivery from aircraft application equipment (i.e., plugged the system), the oil concentration was reduced to 20% for tests using aerial applications. In October 1979, an Experimental Use Permit (EUP) was issued by the EPA for testing AC 217,300 on 10,000 acres (4,000 ha) for the remainder of 1979 and 100,000 acres (40,000 ha) in 1980. Under the EUP, AC 217,300 was distributed to participating personnel of the USDA-ARS, USDA-APHIS, and cooperating state agencies. Excellent results in these field evaluations led to a conditional registration for AC 217,300 formulated in a soybean oil-defatted corn grit bait known as Amdro. It was approved August 1980 for use against imported fire ants on pastures, range grasses, lawns, turf, and nonagricultural lands (Williams 1983). Thus, in less than 2.5 years after registration of mirex was canceled, a new chemical was discovered, tested, and made available to the public as a bait for the control of imported fire ants with additional baits registered soon thereafter (Fig. 11).

During the 1980s, chemicals other than hydramethylnon were showing promise as potential toxicants in imported fire ant baits. Some of these eventually would become registered for use whereas others would go through the long process of development and testing only to be discontinued for one reason or another. For example, Williams and Lofgren (1981) reported that a new chemical from Eli Lilly, EL-468 (a phenylenediamine), was effective in both laboratory and field studies against *S. invicta.* The chemical also was formulated in a soybean oil-pregelled defatted corn grit bait and given the trade name, Bant. But at the

Fig. 10. *Solenopsis invicta* worker carrying a bait particle of defatted corn grit with soybean oil and toxicant.

Fig. 11. Amdro, Logic, and Affirm (Ascend), imported fire ant baits that were developed as replacements for mirex bait. The baits consist of the active ingredients (small white powder, right foreground) dissolved in soybean oil (beaker in middle) and applied to defatted corn grits (material on plate on left foreground).

point of registration, toxicological studies revealed possible teratogenic effects, and it was withdrawn and all research and development were stopped (Lofgren 1986c). Another product, Prodrone, which was an insect growth regulator (IGR), was granted conditional registration by the EPA in 1983, but, because of its inconsistent results and the long time interval for obtaining control, it never gained widespread use (Banks 1986) and soon was phased out. Another IGR, Maag RO 13-5223, gave excellent results in laboratory and field tests (Banks et al. 1983, 1988; Banks 1986; Phillips and Thorvilson 1989). This chemical, called fenoxycarb, is an ethyl carbamate that produces IGR effects in *S. invicta* and other insects (Glancey et al. 1990). Glancey et al. (1989) demonstrated the deleterious effects of fenoxycarb on the queen reproductive system of this ant. The product is formulated in baits called Logic and Award by Novartis Crop Protection of Greensboro, NC. It was registered by the EPA for use against imported fire ants in late 1985. For a review of the development of IGRs as baits against this ant, also see Banks (1986) and Banks et al. (1978).

Another compound demonstrating potential during this time was avermectin B_1a. This compound was one of eight macrocylic lactone glycosides, called avermectins, that were isolated from the soil microorganism *Streptomyces avermitilis* (Burg et al. 1979, Miller et al. 1979, Putter et al. 1981). Fritz et al. (1979) showed that avermectins act as a chloride channel agonist and open chloride channels but have no effect on cholinergic nervous systems. Recent evidence indicates a glutamate-gated chloride channel is activated by several avermectins that may be primarily responsible for muscle paralysis in insects (Bloomquist 1996). Against *S. invicta,* avermectin B_1a is effective at low dosages of approximately 50 mg of active ingredient per acre (Lofgren and Williams 1982). Glancey et al (1982) reported on the deleterious effects of abamectin on the ovaries of *S. invicta* queens. At high concentrations, it also kills worker ants. It was registered for use in April 1986 as a bait initially with the trade name Affirm but now is known as Ascend (Whitmire Micro-Gen, St. Louis, MO), Clinch, and Varsity (Novartis Crop Protection, Greensboro, NC).

Vander Meer et al. (1985b) reported the discovery of a new class of delayed toxicant chemicals, the fluroaliphatic sulfones, that showed excellent control of *S. invicta* in laboratory and field tests (Williams et al. 1987). One compound, AI 3-27757 (sulfluramid), was selected for further development by Griffin Corporation, Valdosta, GA. Field trials with this chemical formulated in a bait gave 80-99% reductions in population index ratings (Banks et al. 1992). Sulfluramid is registered in the United States for control of imported fire ants indoors in containerized bait stations. This chemical replaced mirex in baits used for the control of leaf-cutting ants in South America and is sold in Texas under a special local needs label as the product Volcano.

Although the major research efforts on chemical bait development for *S. invicta* declined because of the availability of several baits for public use, some research continued especially on new chemicals such as IGRs and chitin synthesis inhibitors (CSI). For example, beginning in the mid-1980s, laboratory and field tests with the juvenoid pyriproxyfen (Sumitomo S-31183, Sumitomo Chemical, Osaka, Japan) showed promise with *S. invicta* population reductions of 91-97% in spring and summer treatments (Banks and Lofgren 1991). Glancey et al. (1990) reported that treatment with this chemical caused extensive egg resorption in queens and produced queen sterility. Pyriproxyfen finally was registered for use in July 1998 and is marketed as Distance Fire Ant Bait in the United States by Valent Corporation, Walnut Creek, CA, and as Spectracide Fire Ant Bait by Spectrum Group, St. Louis, MO.

During the 1990s, other chemicals such as methoprene, boric acid, teflubenzuron, spinosyn, and fipronil were tested for use in baits to control *S. invicta*. Methoprene, administered to colonies, causes cessation of egg laying by queens, causes increase in sexual brood production, interferes with embryonic development and metamorphosis, and causes ultimate death of the colony (Cupp and O'Neal 1973, Troisi and Riddiford 1974, Vinson and Robeau 1974, Vinson et al. 1974). Recently, Drees and Barr (1998), showed that methoprene, in laboratory and field tests, performed as well as the commercially available bait Logic, containing fenoxycarb, against populations of *S. invicta*. The methoprene bait (Extinguish, Wellmark International, Bensenville, IL) received a registration in May 1998 for use against imported fire ants in many habitats such as croplands, in which other fire ant baits can not be applied.

Boric acid is an old compound that has been used for controlling insects for many years. It is one of the oxides of boron and seems to act as a stomach poison, but the exact mode of action has not been determined. Six different reports on the efficacy of boric acid against *S. invicta* have concluded that, although some worker mortality oc-

With the development of toxic baits, the broadcast application of these baits was and is today the most effective method of controlling fire ants, especially over large areas. It also is the most efficient method of maintaining control for longer periods

curs following ingestion, an 18% bait formulation has not been effective in eliminating *S. invicta* colonies (Lemke et al. 1985, Porter 1988, Diffie et al. 1988, Diffie 1991, Drees et al. 1992). However, recent work by Klotz et al. (1997) indicates that good results are obtained (90% control of laboratory colonies) when the concentration of boric acid in the bait is 1.0% or lower and formulated in a sugar-water solution. There is one bait containing 18% boric acid (Bushwhacker, Bushwhacker Associates, Galveston, TX) that has been sold specifically for imported fire ants (Drees et al. 1992).

Teflubenzuron (Nomolt—American Cyanamid Company, Parsippany, NJ) is a chemical that belongs to the benzoyl urea group of compounds. Although it is not registered for use in the United States, baits containing this chemical gave 83 to 86% control after 13 weeks and as high as 91% control within 17 weeks following treatments of *S. invicta* populations in the field (Williams et al. 1997).

Spinosyn is a chemical class derived through the fermentation of a naturally occurring bacterium, *Saccharopolyspora spinosa* Mertz and Yao (Cooper and Blewett 1998). When spinosyns A and B are combined, the combination is called spinosad, a product of Dow AgroSciences LLC, Indianapolis, IN. Spinosad is the active ingredient in imported fire ant baits such as Eliminator Fire Ant Bait, Justice Fire Ant Bait, and Strike Fire Ant Bait. A suspension concentrate of spinosad also is registered for use against imported fire ants on lawns and around ornamental plants. Field trials conducted in 1998 by several cooperators using broadcast applications of a 0.015% bait applied at 3 lb/acre (1.36 kg/0.4 ha) gave 79% control 35-44 days after treatment (Cooper and Blewett 1999). However, field trials showed erratic control with all formulations and rates when this product was applied during the spring of the year (Barr 2000). For additional information on this product, see the March and July issues of Fire Ant Trails, Texas A&M University Extension Service (Drees 2000a, 2000b).

Another chemical, fipronil, has given excellent results with a 15 ug/mg (AI) granular bait applied at either 1.7 or 3.4 kg formulated bait per hectare, providing over 80% colony mortality 6 and 12 weeks after treatment (Collins and Callcott 1998). In addition, Sparks and Diffie (1998) obtained over 96% control of *S. invicta* throughout a 30-week trial with a broadcast application of fipronil granular (0.1%) at rates of 0.01875 lb and 0.0250 lb (AI)/acre. Thus, this compound can be formulated either as bait or as a contact granular insecticide, a unique characteristic because most chemicals used in fire ant baits are only efficacious as a bait. Fipronil is a phenyl pyrazole insecticide that blocks the passage of chlorine ions by interacting with gamma-aminobutyric acid-gated chloride channels. Fipronil recently received registration (December, 2000) for use against imported fire ants in a bait formulation and in a contact granular formulation that is incorporated into potting media used for containerized nursery stock. For additional information on the development of toxic baits, see the reviews by Lofgren et al. (1975), Williams (1983), Banks et al. (1985), Lofgren (1986c), Banks (1990), and Collins (1992).

There are dozens of insecticide formulations on the market under numerous trade names with several having the same active ingredient. Public confusion as to which chemical should be used for the control of imported fire ants is common. Along with the array of products from which to choose (Fig. 12), there is also a misunderstanding about application techniques, timing of application, and efficacy of the products. For excellent reviews of various control methods and options, readers should see Hamman et al. (1986), Drees and Vinson (1993), Oi et al. (1994), Drees et al. (1996, 1998, 2000), and Drees and Summerlin (1998). In addition, there are several fact sheets on control of *S. invicta* available on websites such as (http://fireant.tamu.edu) maintained by Texas A&M University and (http//www.uaex.edu) maintained by the University of Arkansas.

The first method of control of imported fire ants was treating individual mounds with contact insecticides (Fig. 13). This was followed by the use of broadcast applications of these contact chemicals. With the development of toxic baits, the broadcast application of these baits was and is today the most effective method of controlling fire ants, especially over large areas. It also is the most efficient method of maintaining control for longer periods (Lofgren and Weidhaas 1972; Williams 1983, 1994; Banks 1990). Broadcasting baits to large areas also is better for slowing migration of colonies into treated areas from untreated ones. Although newly mated queens from mating flights will reinfest a recently treated area, several months are required before these new queens will produce colonies of sufficient size to be noticeable (Callcott and Collins 1992, Collins et al. 1992). Concurrently, with the development of post-mirex baits, a variety of contact insecticides has been formulated for *S. invicta* control (Sheppard 1988, Drees and Vinson 1993, Drees and Summerlin 1998, Collins and Callcott 1995). These contact insecticides usually kill ants quickly, but, in many cases, they do not kill the queen, and the colony survives and reestablishes. However, if applied appropriately, a majority of the ants in a colony can be killed quickly. This reduces the potential danger from stings much

Fig. 12. An array of bait products registered for use against imported fire ants. Not all registered products are shown.

Fig. 13. Drenching an individual *Solenopsis invicta* mound with a contact insecticide in Gulfport, MS. Note, because of the radiating foraging tunnels, standing close to a mound could result in stings.

faster than baits. To take advantage of the thoroughness of baits and the fast reductions by contact insecticides, a two-step method in which baits are applied first followed by a contact insecticide has been recommended for control of this ant in urban areas (Drees et al. 1996). This is because foraging workers that collect the baits need time to spread them throughout the colony before the fast kill contact insecticides are applied.

In conclusion, *S. invicta* has had a substantial impact in the United States on humans, agriculture, and wildlife with economic costs of one-half billion to several billion dollars per year (Thompson et al. 1995, Thompson and Jones 1996). The most harmful problem caused by this ant is its stinging of humans that, in some cases, has caused serious injuries and even death to hypersensitive individuals (Kemp et al. 2000).

The continuous urbanization of the United States, migration of people to the Sun Belt states, and expansion of *S. invicta* populations almost guarantees an inevitable contact between the two. This escalating contact between people and this ant elevates public health problems, and stronger demands are made for controlling this pest. Thus, more effective and safer management techniques will be required to suppress or eliminate *S. invicta* in a variety of situations and habitats.

The development of new technologies utilizing multiple strategies will be important for the future management of *S. invicta*. These could include effective biological control agents, biopesticides, semiochemicals (pheromones) used to disrupt colony organization, genetic and molecular manipulation of colony organization, exploitation of male sterility, utilization of competitive ant species, and the development of better physical methods of control. In addition, the requirement to keep this species from entering occupied dwellings will require the development of *S. invicta* repellents and safer residual contact chemicals that can used as perimeter treatments. We must use multiple control strategies for a coordinated and integrated management system that will have as its goals the reduction of *S. invicta* throughout the infested area of the United States and its elimination in areas where large numbers of people may be in danger of its stings. Chemicals still will be one of the important tools for its control in the future. This especially is true for those areas considered as significant fire ant risk for humans such as schools, recreational areas, and nursing homes, where the tolerance for fire ants is virtually zero. The high level of control and the speed with which chemicals can eliminate colonies probably will not be attained with biological organisms in the near future. Consequently, chemicals will be a necessary component of any integrated management program for this pest. However, control today and in the future demands that we develop more target-specific, safer, and more environmentally compatible active ingredients and formulations.

Table 1. Summary of historical events in imported fire ant control (revised from Williams 1983)

Year	Event
1929-1940	Discovery and establishment of *Solenopsis invicta* in the United States at Mobile, AL.
1949-1953	Rapid dispersal of *S. invicta* throughout the south eastern United States from shipment of nursery stock from the infested area.
1957	Cooperative federal-state control program initiated.
1952-1962	Use of heptachlor and dieldrin for areawide eradication.
1962	Mirex becomes standard eradication treatment replacing heptachlor and dieldrin.
1962-1978	Over 140 million acres of land treated with mirex bait.
1973-1980	USDA conducts large scale evaluation of chemicals as possible replacement for mirex in baits.
1978	All registrations for the use of mirex canceled by the EPA.
1979	Experimental use permit issued for large area testing of hydramethylnon as a bait for imported fire ants.
1980	Conditional registration for Amdro (hydramethylnon) for use against imported fire ants on pastures and range grasses, lawns, turfs and non-agricultural lands.
1983-1986	Conditional registration of the first two insect growth regulators for use against imported fire ants, ProDrone and Logic (fenoxycarb) and registration of the avermectins (Affirm, now called Ascend). Also, report of the discovery of new delayed action toxicants, the fluroaliphatic sulfones (sulfluramid). Initial tests also were being conducted with the juvenoid pyriproxyfen.
1990-1999	Distance (pyriproxyfen), Extinguish (methoprene), and Eliminator (spinosad) received registrations for use as baits against imported fire ants. Field tests with fipronil show excellent activity against *S. invicta*.
2000	Registration of fipronil for use against imported fire ants.

Research programs before 1975 focused primarily on the development of chemicals for control because of the need for quick elimination of imported fire ant colonies and, thus, relief from these pests even when treatments lasted only for a short time. The success of discovering new chemicals, formulations, and delivery systems has been outstanding. Table 1 summarizes the historical path of this development. Unfortunately, imported fire ants still are with us and will be with us in the foreseeable future. Beginning in the late 1970s and continuing to the present, research concentrated not only on the development of chemical control but on the biology, ecology, and behavior of this pest. It became obvious that newer methods of control that utilized biological and biorational approaches that would have less impact on the environment needed to be developed, and this has become a high priority among researchers of imported fire ants.

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David F. Williams is a research entomologist in the Imported Fire Ant and Household Insects Research unit and lead scientist on the biological control of fire ants at the Center for Medical, Agricultural, and Veterinary Entomology, USDA-ARS, P.O. Box 14565, Gainesville, FL32604 (dwilliams@gainesville.usda.ufl.edu). He has worked on the biology and control of fire ants for over 25 years, was involved in the development of most of the commercially available fire ant baits, and is currently involved in fire ant biological control research. **Homer L. Collins** is retired Station Leader of the Imported Fire Ant laboratory, USDA-APHIS-PPQ, Gulfport, MS 39503 (hcollins@datasync.com). He was involved for over 30 years on the development of control methods for imported fire ants and is currently a consultant. **David H. Oi** is a research entomologist in the Imported Fire Ant and Household Insects Research unit at the Center for Medical, Agricultural, and Veterinary Entomology (doi@gainesville. usda.ufl.edu). He has conducted research on fire ants for over 10 years and currently is working on the development of pathogens, especially *Thelohania solenopsae,* as biological control agents for fire ants.