CONTROLLED RELEASE FORMULATIONS AND CONTROL OF THE IMPORTED FIRE ANT: WHAT ARE THE POSSIBILITIES

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The imported fire ant, *Solenopis invicta*, infests large areas of 9 southeastern and southern states. The importance of the ant as a pest and its unique foraging habits offer a tremendous challenge to controlled release technology. The present paper presents background information, introduces requirements for control of the fire ant, and discusses recent results and future prospects for several types of controlled release systems.

Two species of fire ant, *S. invicta* and *S. richteri*, were accidently imported into the United States at Mobile, Alabama, about 40 and 60 years ago, respectively. The more aggressive *S. invicta* has proved to be the most important of the two, and has spread rapidly over most of the South (Figure 1). *S. richteri* occupies small areas in northern Mississippi and Alabama. The major factors that now limit further migration of the ants are the cold, northern winters and the desert areas of central Texas.

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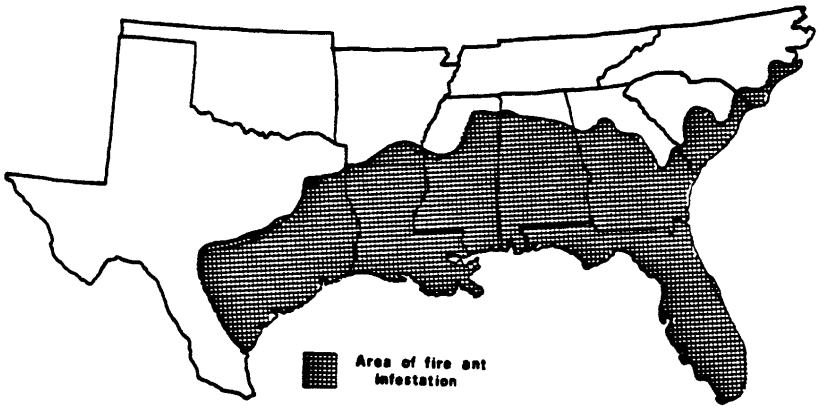


FIGURE 1. Infestation of Solenopsis invicta in the United States.

Initial efforts at developing control methods were begun in the early 1950's (Table I). However, the rapid spread of *S. invicta* into grazing and croplands, roadsides, parks and lawns, along with their mound-building, aggressive behavior and potent sting caused such great concern among the general public and farmers that a cooperative federal-state program was instituted by the U.S. Congress in 1957.

Based on earlier work in Alabama (1, 2), granular formulations of heptachlor and dieldrin were used to obtain long-term residual control of fire ants. However, in the late 1950's and early 1960's, the attention of the public and the scientific community was focused on the detrimental effects of these residual chlorinated pesticides, and their use was greatly restricted (3). Consequently, in 1962 these chemicals were replaced with a newly-developed bait formulation consisting of mirex dissolved in soybean oil and applied to a corncob grit carrier (4, 5). Although mirex was another chlorinated hydrocarbon, it was considerably less toxic to non-target organisms than dieldrin and heptachlor (6). It was very effective. As a result, over 140 million acres of land were treated with mirex from 1962 to 1978. Research during the same period resulted in reductions in the amount of the toxicant required for control from 4.2 to 0.46 g/acre. However, in 1978 the Environmental Protection Agency canceled the registration for mirex because residues of the chemical were being found in the environment (7) and in human tissues (8). Also, laboratory studies suggested it might be a

TABLE I. Important Historical Events in Control of the Imported Fire Ant (Solenopsis invicta).

Year	Event
1940	Accidental introduction of Solenopsis invicta into the Mobile, Alabama, area.
1949-1953	Surveys of nurseries showed rapid dissemination of S. invicta in southeast U.S. due to shipment of infested plants from Mobile, Alabama, area.
1957	Federal-state control program initiated.
1952-1962	Heptachlor and dieldrin used for long-term residual control.
1962	Mirex replaced heptachlor and dieldrin.
1962-1978	Over 140 million acres of land were treated with mirex.
1978	Mirex registration cancelled by the EPA eliminating the only chemical registered for control of fire ants on farmland.
1979	Experimental use permit issued by EPA for field testing American Cyanamide 217,300, a new bait toxicant.

carcinogen (9,10). The ban on mirex as a control agent for fire ants, particularly on farm land, has left a void that we are working hard to fill.

The difficulty in finding suitable insecticides for use in baits for fire ants is directly related to the behavior and ecology of the insect. Foraging worker ants, only a small fraction of a colony's population, leave the central nest through a system of radiating tunnels (Figure 2). These tunnels can extend as far as 15-30 m with outlet holes to the foraging area surface about every 30 cm. By using this foraging scheme, the ants thoroughly search the area around a mound for food sources. Once a foraging ant locates food,

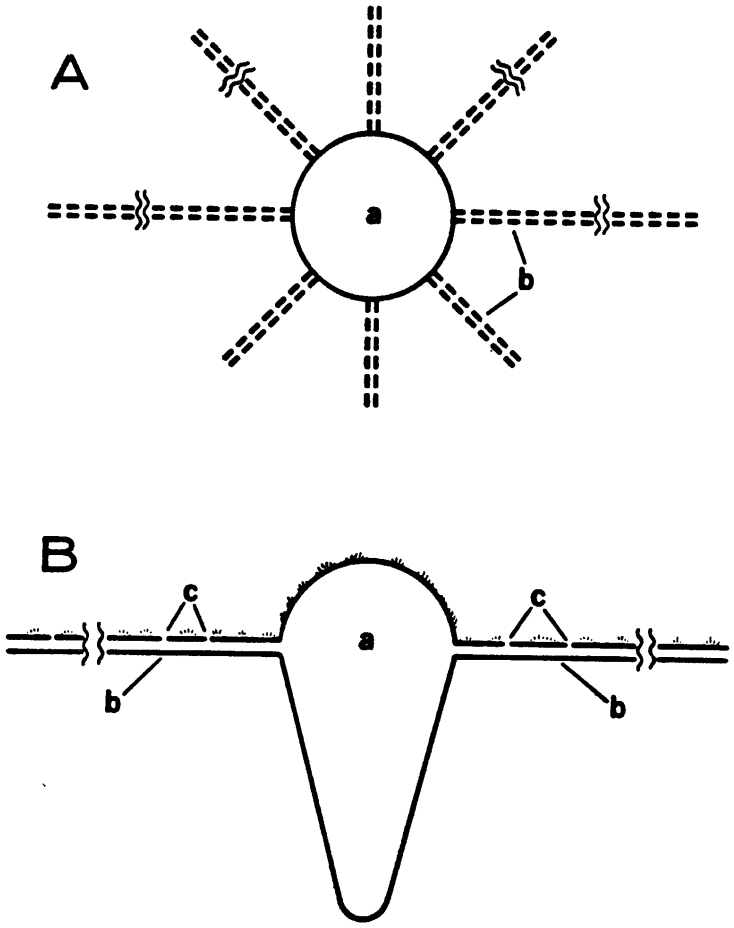


FIGURE 2. Fire ant mound diagram. Top view (A) and cross section (B), showing mound (a), radiating foraging tunnels (b), and outlets to the foraging areas (c).

it returns to the foraging tunnel and nest laying a trail with the trail pheromone. In this way other workers are recruited to the food source and a continuous stream of ants soon develops between the food and nest. The foraging ants store food in their crops, and through regurgitation and food exchange (trophallaxis), they quickly disperse the material to other members of the colony (11).

Two major qualifications for a toxicant are apparent. If the toxicant acts too quickly, the foraging workers will die before they can distribute the material to other members of

the colony and ultimately to the queen. Therefore, delayed toxicity is required. Tests with dyed soybean oil indicated that complete colony distribution is achieved within 24-72 hr. Secondly, the process of trophallaxis greatly dilutes a toxicant (a mature colony may contain more than 250,000 workers) making it necessary to have delayed toxicity over a wide range of dosages (preferably > 100).

Currently, the Insects Affecting Man and Animals Research Laboratory in Gainesville, Florida, and the USDA Imported Fire Ant Research Laboratory in Gulfport, Mississippi, are actively conducting research to develop new control methods based on a sound knowledge of the biology, ecology and biochemistry of the fire ant. Included in this holistic approach is the search for pathogens of *S. invicta* in its native South American habitat. Also, we have bioassayed over 5000 potential toxicants and are actively looking for additional candidates. Among these are traditional toxicants, insect growth regulators, chitin inhibitors, and sterilants.

For much of this work we depend on the following procedure developed for the rapid laboratory screening of candidate toxicants: The toxicant is dissolved to the desired concentration in either soybean oil or honey-water (1:1) depending on its solubility. Test groups of 20 worker ants are allowed to feed for 24 hr on cotton swabs saturated with the formulation. After 48 hr, the ants are fed unadulterated soybean oil. Mortality counts are made at 1, 2, 3, 6, 8, 10 and 14 days after the initial exposure. Each material is tested at 3 concentrations: 1, 0.1 and 0.01% (12).

All chemicals tested are classified according to the scheme shown in Table II. Class II compounds are good toxicants but they do not have the required delayed toxicity, whereas class III compounds have delayed action, but their range of activity is too narrow. The type of activity we are looking for in a toxicant is exemplified by a class IV or V response, i.e., it exhibits delayed toxicity over a wide range of concentrations.

As expected most of the 5000 compounds screened (Table III) fall into the non-toxic class I category. Most of the 20 class IV compounds are organophosphorous insecticides that did not work well in field tests or are derivatives of mirex, including ACD-1189 (known as Kepone). As expected the only class V compound is mirex.

Of primary interest to this symposium is our effort to utilize the information gained through our basic physiological studies and intensive screening program to support

TABLE II. Classification System for Imported Fire Ant Bait Toxicants

Class	Definition
I	*Compounds that give insufficient kill at the preliminary concentrations (less than 90% at the end of the test period).*
II	*Compounds that kill too quickly at the higher concentrations but give insufficient kill at the lower concentrations, that is, higher concentrations give 15% or more kill after 24 hr and 90-100% at the end of the test period, but lower concentrations give less than 90% kill at the end of the test period.*
III	*Compounds that show no greater than a 9-fold difference between the minimum and maximum concentrations that exhibit delayed toxicity.*[a]
IV	*Compounds that showed at least a 10-fold but not greater than 99-fold difference between the minimum and maximum concentrations that exhibited delayed toxicity.*
V	*Compounds that show at least a 100-fold difference between the minimum and maximum concentrations that exhibit delayed toxicity.*

[a]*Delayed toxicity is defined as mortality of less than 15% after 24 hr and more than 89% at the end of the test period.*

research projects whose aim is to modify or formulate fast-acting toxicants into delayed-action materials. The possibilities presently considered can be categorized as in Table IV.

Matrix bound and microencapsulated toxicants (A and B) have several similarities. Both are presented to the ants as a solid formulation dispersed in soybean oil. Ideally, after ingestion and dispersal within the colony, lethal concentrations of toxicant will gradually build up via diffusion

TABLE III. Laboratory Evaluation of Bait Toxicants Against Imported Fire Ants

Class	No. of chemicals tested	Percent of chemicals in class
I	4269	87.0
II	374	7.6
III	255	5.0
IV	20	0.2
V	1	0.02
Total	4919	

to the surface of the matrix or through the wall of the microcapsules. Another possible release mechanism depends on the composition of the matrix or wall material, since toxic concentrations can also be released through chemical or enzymatic degradation of the polymer used.

In collaboration with USDA and private laboratories we have tested several formulations of both types. The results (Tables V and VI) have touched the two extremes—either very rapid kill similar to that of the unformulated compound or no appreciable effect. We had estimated from research with electron microscopy that particles 5 μ or less would easily pass into the ant's digestive system. This size constraint is achievable for both microcapsules and microparticle matrixes. However, we have recently discovered that worker

TABLE IV. Four Methods of Modifying or Formulating Fast-Acting Toxicants into Delayed-Acting Materials

A. Matrix bound toxicants
B. Microencapsulated toxicants
C. Modification of toxicant structure
D. Pendent toxicants

TABLE V. Results When Matrix Bound Toxicant Formulations Were Tested Against S. invicta Workers.

Matrix bound toxicant	Matrix	Concn. (%)	Percent kill after indicated number of days						
			1	2	3	6	8	10	14
Coumaphos[a]	Polystyrene	0.01	0	2	2	2	2	3	13
		0.1	25	70	83	93	93	100	
		1.0	42	92	98	98	98	98	98
Coumaphos[a]	Polymethylmethacrylate	0.175	88	98	98	100			
Coumaphos[a]	Polymethyl-acrylate	0.19	2	2	2	3	3	5	12
		0.38	83	87	87	90	90	95	95
		0.75	100						
Coumaphos[b]	Natural polymer	1.0	98	100					
		2.0	98	100					
Trichlorfon[c]		0.1	0	0	0	0	2	2	3
		0.5	5	12	12	13	13	15	20

[a]Formulations supplied by Dr. J.P. Kochansky, USDA, Beltsville, MD.
[b]Formulation supplied by Griffith Laboratories, Chicago, IL.
[c]Formulation supplied by Dr. E. Gabbay, Chemistry Department, University of Florida.

TABLE VI. Results of Microencapsulated Toxicant Formulations against S. invicta Workers.

Encapsulated toxicant[a]	Concn. (%)	Percent kill after indicated number of days						
		1	2	3	6	8	10	14
Ethyl pirimiphos[b] (3.5 µ)	0.01	78	85	100				
	0.1	100						
	1.0	100						
Methyl pirimiphos[b] (4.2 µ)	0.01	7	12	18	22	23	25	35
	0.1	60	100					
	1.0	100						
Permethrin[b] (4.9 µ)	2.0	8	20	22	22	22	22	23
Diazinon in honey-water[c] (4 µ)	0.01	0	0	2	12	13	22	40
	0.1	100						
	1.0	100						
Diazinon in soybean oil[c] (4 µ)	0.01	2	3	10	15	22	27	37
	0.1	13	33	67	98	98	98	100
	1.0	92	100					

[a]Numbers in parentheses = mean particle size.
[b]Formulations supplied by ICI Americas.
[c]Numbers in parentheses = mean particle size.

ants have a very sophisticated mechanism for preventing solid particles from passing into the pharynx and esophagus. Food material is compressed in the infrabuccal pocket with liquids forced through a series of hairs or setae; this traps particles before they have a chance to enter the pharnyx (Figure 3). The liquid then moves on to the crop and/or digestive tract. When the infrabuccal pocket is filled with solids the compressed mass is expelled in the form of a pellet.

Studies with fluorescent latex microspheres have shown that particles as small as 0.88 μ (Table VII) in diameter are trapped by the filtration mechanism. Since this size approaches the limit of light microscopy, we do not know how small the particles must be to readily pass through the filter. A similar filtration mechanism is known for another ant, *Camponotus americanus* (13). However, in this case, particles under 100 μ readily passed through to the crop. Therefore it is reasonable that fast toxic action with the matrix and encapsulated formulations is caused by the insecticide contaminating the surface or by its rapid diffusion into the soybean oil or honey-water solution. Lack of toxicity with the formulation is simply due to the particles being filtered. This ultra-fine filtration mechanism

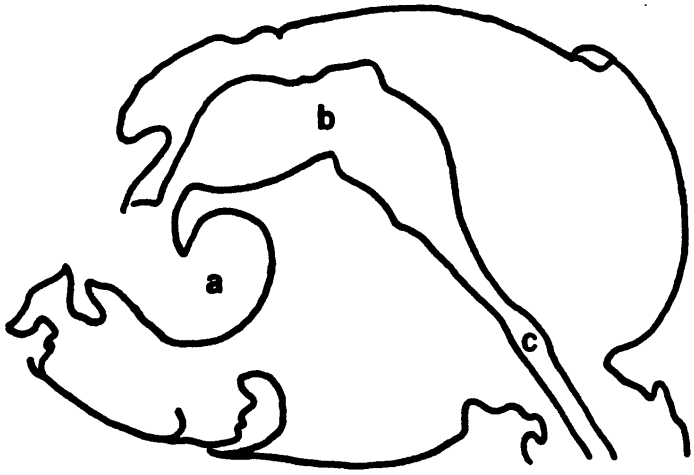


FIGURE 3. Diagram of an ant head showing (a) infrabuccal pocket, (b) pharynx, and (c) esophagus.

TABLE VII. Microfiltration by Fire Ant Workers. Analysis of Ants Fed Honey-Water Containing Fluorescent Microspheres

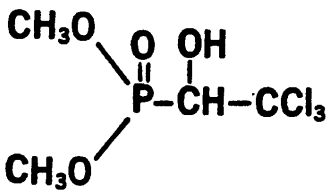
Microsphere size (μ)	No. ants examined	Avg. no. particles/microscopic field	
		Crop[a]	Infrabuccal pocket[b]
0.88	5	3.16	77.28[c]
1.8	8	0.002	44
4.6	5	0.007	26.0

[a]Total sample area examined.
[b]Five microscopic fields per ant examined.
[c]Buccal pellet ejected in 3 cases. One pellet count = 1760 particles.

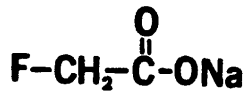
of the ants appears to make utilization of the matrix and microencapsulation approaches impractical. However, we are still investigating the possibility that the type of polymer or wall material may influence acceptance and ingestion.

Method C, the modification of a toxicant structure (Table IV), is defined as the chemical alteration of a known fire ant toxicant (preferably a class II compound) to a relatively nontoxic material that is so structured that the parent toxicant can be regenerated by an enzymatic or hydrolytic mechanism present in the ants. This pro-agent approach has been well developed in the pharmaceutical industry (14) and has also led to remarkable selective activity in some herbicides and insecticides (15).

The commercially available insecticides are conspicuous for their lack of functionality required for simple modification. Only trichlorfon has a functional group capable of forming an ester linkage (Figure 4). Therefore, in collaboration with the USDA Insect Physiology Laboratory in Beltsville, Maryland (16), we attempted to design delayed action toxicants using trichlorfon and sodium fluoroacetate as precursors (Figure 4). (Although sodium fluoroacetate is too highly toxic to mammals for practical use, it is a good model for studying the feasibility of this approach).



triclorfon



sodium fluoroacetate

FIGURE 4. Structures of trichlorfon and sodium fluoroacetate.

Trichlorfon esters were prepared by reaction in ether with the appropriate acid chloride and pyridine. Esters of fluoroacetic acid were prepared by reaction with phosphoryl chloride followed by the addition of the appropriate alcohol and pyridine. The results (Tables VIII and IX) show that delayed toxicity was achieved with the caprate ester of trichlorofon and the two sterol esters of fluoroacetic acid. Unfortunately the range of toxicity is too narrow; therefore, in effect, we had changed class II compounds into class III compounds. Although these experiments did not yield the perfect delayed toxicant, they illustrated the feasibility and potential of the approach.

The pendent toxicant method for slow release has been successfully utilized in the area of controlled release herbicides (17,18). This approach is similar to that of pro-toxicants since the active agent is slowly released as the covalent linkages are hydrolyzed in the digestive system of the ant. Our laboratory has been interested in pendent toxicants for some time, and in September 1978, researchers at the Southern Research Institute, Birmingham, Alabama, were given a USDA Grant that allowed them to embark on a pendent toxicant feasibility study. Preliminary results look encouraging, and we will present a full description of the work next year.

In summary, matrix-bound and microencapsulated toxicants probably cannot be used for controlled release of toxicants against fire ants because of the remarkable filtration mechanism found in the ants. Structure modification of existing insecticides to form pro-toxicants has shown promise in achieving a degree of delayed toxicity. Although this approach is greatly limited by the lack of insecticides with suitable functional groups, we hope work in this area will continue.

This paper reports the results of research only. Mention of a pesticide in this paper does not constitute a recommendation for use by the U.S. Department of Agriculture nor does it imply registration under FIFRA as amended.

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TABLE VIII. Toxicity of Trichlorfon and its Esters When Fed in Soybean Oil to S. invicta Workers.[a]

Compound	Concen.	Percent kill after indicated number of days						
		1	2	3	6	8	10	14
Trichlorfon	0.01	7	12	15	23	23	23	25
	0.1	95	98	98	98	98	98	98
	1.0	100						
Caproate	0.1	0	0	1	6	10	11	14
	1.0	12	28	44	57	61	66	67
Caprate	0.1	1	1	2	4	4	6	10
	1.0	5	30	53	79	82	83	86
	4.0	26	39	39	45	46	49	49
Myristate	0.1	0	0	0	2	3	3	8
	1.0	5	22	42	67	68	72	75
	4.0	15	25	37	40	40	40	40
Stearate	0.01	0	0	1	2	5	6	10
	0.1	2	3	9	24	26	29	35
	1.0	46	79	95	96	98	99	99

[a]Kochansky et al. (16).

TABLE IX. Toxicity of Fluoroacetyl Derivatives when Fed in Soybean Oil to S. invicta Worker Ants[a]

Compound	Concen. (%)	Percent kill after indicated number of days						
		1	2	3	6	8	10	14
Sodium fluoroacetate[b]	0.01	3	8	15	22	22	23	25
	0.1	88	100					
	1.0	100						
Cholesteryl fluoroacetate	0.01	2	3	3	4	4	6	10
	0.1	0	0	0	2	2	3	6
	1.0	3	15	38	84	91	95	100
	4.0	88	98	98	100			
Sitosteryl fluoroacetate	0.01	2	2	5	9	11	13	22
	0.1	1	2	2	9	13	19	37
	1.0	7	21	42	66	79	87	96
	4.0	23	37	58	78	87	90	93
Octadecyl fluoroacetate	0.01	0	1	1	6	10	11	15
	0.1	1	1	2	17	33	44	62
	1.0	98	99	99	99	99	99	99

[a]Kochansky et al. (16).
[b]Fed to the ants in a honey-water solution.

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