The IPM Practitioner
Monitoring the Field of Pest Management
Volume XIV, Number 5/6, May/June 1992

DIATOMACEOUS EARTH FOR PEST CONTROL.

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Least toxic physical and chemical solutions are often part of an IPM program. Various forms of amorphous silica are commonly used as part of this strategy. Diatomaceous earth and silica gel are used in various physical formulations with or without added pesticide. The type of silica and the formulation depend on the target pest. In this issue advantages and disadvantages of diatomaceous earth are discussed. In July the merits and uses of silica gel will be outlined.

Diatomaceous earth (DE) is a non-toxic insecticide that is used for protection of stored products, and to control pests of the home and garden. Organic gardeners like it because it is a natural product that poisons neither the earth nor people. Pest control operators (PCOs) like it, because diatomaceous earth can be used to treat wall voids and other inaccessible regions of a house in order to deny harborage to pest insects. Also, PCO's that use least-toxic products are able to address homeowner concerns about poisons in a positive way.

Diatomaceous earth is obtained from deposits of diatomite - fossilized sedimentary layers of tiny phytoplankton called diatoms, many of them originating at least 20 million years ago in the lakes and seas of the Miocene (see Box A for more information on diatoms). The developing North American continent was full of these organisms that ingested dissolved silica and converted it into a highly ordered shell. Diatoms that lived in prehistoric seas are now mined mostly in Lompac, California as Celite ® and fossilized freshwater species are found in such places as California, Oregon, Nevada and Arizona (Cummins 1975).

Whether marine or freshwater fossils are better for insect control work has been recently debated. Freshwater fossils met with early commercial success, and are easier to apply without clumping or caking. Any diatomaceous earth with a large oil absorption capacity, though, is a candidate for use as an insecticide. Ideally, it should be a high purity amorphous silica of a uniformly small (less then 10/u) particle size, that contains very little clay, and less than 1% crystalline silica. The diatomite should be properly milled and ground, the diatoms well-separated, and if possible, physically intact (Katz 199aa; Calvert 1930; Allen 1972). Any product registered with the EPA has to meet the proper standards. This kind of material is easier to obtain from freshwater fossil sources because much of the marine diatomite is calcined (glassified by high temperatures) in order to improve its filtration characteristics (Calvert 1930).

Calcined fossils are often sold for use in swimming pool filters. Such material has little absorptive power, and is not useful as an insecticide (see Common Sense Pest Control Quarterly 3(1):14-16). High temperature (800 degree C) also converts amorphous silica into crystalline silica, and some grades of diatomite on the market may contain up to 60% of this material. Crystalline silica, when inhaled can cause the deadly disease silicosis or other respiratory problems (Katz 1991a; Diafil 1992; Abrams 1954)

Both silica gel and diatomaceous earth are forms of amorphous silica, and they both kill insects by desiccation, not by absorbing water, but by absorbing the oily or waxy outer cuticle layer by direct contact. When the thin (about 1/u) waterproof layer of the epicuticle is lost, the insect loses water, then dies. Abrasive damage to the cuticle also leads to water loss in some cases, but the effectiveness of silica as an insecticide often depends on the amount of oil it can absorb. The ability to absorb oil or wax from an insect, is often, but not necessarily, related to surface area of the silica (Ebeling 1961). Silica gel has the advantage of a much larger surface area than diatomaceous earth, but the latter is more abrasive. Whether the one or the other is used depends on the target insect and conditions (Ebeling 1971).

Diatomaceous earth was improved in 1976 with the invention of Dryacide®. The surface area of the silica was increased by gluing silica gel to it. Trials of Dryacide for wheat protection are discussed later. Another improved material is Shell-shock® invented by Dorsey Dunlap and tested by Robert Snetsinger at the

University of Pennsylvania. Shellshock is diatomaceous earth covered with an adhesive that is formulated for control of insects such as cockroaches and ants. Once an insect comes into contact with Shellshock, it is unable to easily remove it. Lipids and fats are drained from the cuticle, and the insect dies from desiccation (see Common Sense Pest Control Quarterly 7(1):5-20).

Though not used as often as silica gel inside houses, diatomaceous earth is most useful in treating cracks, wall crevices, wall voids, and attics to repel insects and deny harborage in these areas. It is effective against pests that live in close association with humans such as cockroaches, silverfish, mites, ants, houseflies, spiders, bedbugs, fleas and crickets (St. Aubin 1991).

History of Use

Soil and clay dust is often used by birds that take "dust baths" to free themselves of mites and other parasites. This observation may have led the Chinese to use diatomaceous earth (diatomite) for pest control 4000 years ago (Allen 1972). In America, road dust was observed killing cotton worms as early as 1880 (Stelle 1880). Until the 1950's clay dusts, sand, or silica gel were more popular test materials than diatomite. Insects controlled by inert dusts up to 1950 include oriental fruit moth and codling moth larvae, flea beetles, cucumber beetles, cockroaches, Mexican bean beetle larvae, and stored grain pests (Bartlett 1951).

Marine diatomaceous earth was used in many of the early experiments. Pollivka (1931) used diatomaceous earth to suppress field populations of corn borer. Dusting the corn plants had a measurable physiological effect. Sllking was delayed, and for every day's delay in silking, there was a reduction of 4% in the corn borer's population. Chiu (1939a) used salt water diatomaceous earth (Celite® in lab tests against the bean weevil. Aconthoscelides obtectus. Similar tests were made with the rice weevil Sitophilus oryzae, and the granary weevil, Sitophilus granarius (Chiu 1939b). The marine fossils he used were probably calcined, as they were less effective than finely ground (2.9/u) sand.

Diatomaceous earth or silica gel was used to protect beans against the bruchids Callosobruchus chinensis and Acanthoscelides obtectus (Parkin and Bills 1955). David and Gardiner (1950) did laboratory tests using both silica gel and an abrasive diatomaceous earth (Sil-O-Cel) against four stored product pests: Rhyzopertha, Sitophilus (Calandra), Tribolium, and Ptinux. These early experiments and those of Alexander et. al (1944) showed abrasive material of a uniformly small (1-2/u) particle size to be the most adherent and most effective, but the amorphous silica they used may not have had a large enough oil absorption capacity to provide a proper comparison (Ebeling 1971).

Type of Insect Affected

Some insects are more vulnerable than others due to their anatomy and physiology. Those with large surface area to volume ratios (often smaller insects) are more susceptible. Insects such as the merchant grain beetle, Orzyaephilus mercator, that have lots of body hair to pick up particles are more susceptible than smooth beetles such as the confused flour beetle, Tribolium confusum (Carlson and Ball 1962). Insects with thin cuticles such as Aphytis spp. are more susceptible than those with thicker cuticles such as Metaphycus spp. (Bartlett 1951). Insects such as the cockroach that is protected by a low-melting grease are more susceptible than insects with hardened, waxy cuticles (Ebeling 1971). Finally, sucking insects that are constantly obtaining water by feeding on vegetation are less susceptible than those that feed on dry grain (Flanders 1941).

Effect on Beneficials

Dusts in general are repellent to insects. Possible effects on beneficials3 were first noticed when citrus along dusty roadways became heavy infested with mealybugs. Hymenopteran parasitoids that normally destroy scale and mealybugs were being killed or repelled by the road dust. Both codling mother larvae and their enemies are also killed. The beneficials are affected more, however, as orchard infestations of this insect are greatest along dusty roads (Flanders 1941; Callenbach 1940; Driggers 1928).

Beneficials are much more sensitive to fresh dust than to that treated with a fine spray of water to simulate dewfall 24 hours before testing. The LT-50 (time it takes half the exposes population to die) of Aphytis chrysomphali increased from 0.3 hrs. to 12.0 hrs when the diatomaceous earth dust was moistened. The dust regained its toxic effect only partially after 35 days in the laboratory at 50% related humidity (Bartlett 1951).

UPDATE

BOX A. BIOLOGY OF DIATOMS

Though diatomaceous earth is composed of fossilized diatoms, these small creatures have survived with few changes until today. Two major types exist, marine and freshwater. Freshwater diatoms were discovered by Leewenhoek in 1703 before the existence of marine organisms was even suspected. Systematic naming and identification began in 1819. Diatoms are all single-celled organisms, but some are free-living and others live in colonies. They are generally flat, composed of two overlapping valves made of porous silica with many small (.5 to 1.µ) holes. The general construction is similar to that of a petri dish (Cummins 1975). The major species in freshwater fossil samples is the cylindrical *Melostra granulata* which is shown in the photo on the front page. It is 5 to 35µ in diameter, and 9 to 26µ in height. Pores are 50 to 100 mµ in diameter (Calvert 1930).

Diatoms are phytoplankton, actually small plants that are responsible for much of the food and most of the oxygen that is consumed on the earth. About six-tenths of all phytoplankton are diatoms, and the ocean averages 7 to 8 billion per square meter. Plankton diatoms divide once every 18 to 36 hours, and the life cycle of a diatom is about 6 days. Marine diatomaceous phytoplankton are often called "grass of the sea" because many ocean creatures depend on them for food. Masses of them are consumed in the food chain, as it takes 10,000 lb. of diatoms to make 1,000 lbs. Of coepeds, then 100 lbs. Of herring, and finally 1 lb. of tuna fish.

Diatoms filter nutrients from solution, and photosynthesize, releasing oxygen. The product of photosynthesis is a dark-green fishy smelling oil that is chemically more similar to animal than vegetable oil. Diatom oil may be the source of today's petroleum.

Diatoms represent the major way that silicates dissolved from the earth's crust are recycled. Quartz has a solubility of about 10 ppm, while amorphous silica averages around 100 ppm. River waters have about 5 to 35 ppm of dissolved silica. Solubility of silicates is low, but the ocean has 01 to 7 grams per ton of water. Diatoms extract silicic acid, and incorporate it into shell. When diatoms settle to the bottoms of lakes and seas, diatomaceous earth deposits are formed. This silica is often reintegrated under pressure into the earth's crust as sedimentary or metamorphic rock, usually a hard chert consisting of opal or chalcedony.

Deposition rate is slow - 1 foot every 20,000 years. Freshwater deposits occur in streams, swamps, lakes and ponds. Marine deposits were in Moreno shales of the Upper Cretaceous, about 60-110 million years ago. The U.S. deposits occurred during the Miocene epoch, about 20-30 million years ago.

Sedimentary deposits of diatoms are sometimes found in decaying bogs with other plant material. This association with decay led to the term kieselguhr (1808) for diatomaceous earth in Germany. The word comes from the German words kiesel (silica) and guhrer (to ferment). Most everywhere in English speaking countries the deposits are called diatomite. Diatomite was first discovered in America in 1839 in a bog near West Point, New York. It was discovered in California in 1852 near Sulsan Bay, 30 miles north of San Francisco. There are diatomite deposits throughout California, and the largest one is the marine deposit near Lompoc that is responsible for much of the filter aid sold under the brand name Celite™. The first commercial application of diatomite was the manufacture of dynamite in 1865 (Cummins 1975).

Hymenopteran parasitoids are especially sensitive to dust due to specialized structures for removing dust particles. Dust is strained from liquid food and placed in a "gnathal pouch" just beneath the mouth. "When small species of parasitic Hymenoptera such as Trichogramma, come into contact with an excessive amount of dust, their movements lack coordination and they wallow helplessly." (Flanders 1941).

According to Flanders (1941), "the parasites of pests not only may be more susceptible to dusts, but they may be more uniformly affected than their hosts since they are largely hymenopterous or dipterous and consequently are more uniform in structure and in their feeding habits." Excessive application rate is more important than the number of applications in affecting beneficial mortality.

Stored Product Protection

Diatomaceous earth has great potential as a grain protectant. It is non-toxic, provides good protection when grain is stored properly, can be easily separated from the grain, and possibly recycled in storage bins. Toxicity is so low that diatomaceous earth is not counted as a foreign substance when grain is rated by the USDA (Federal Register 1961),

Important factors to be considered when using diatomaceous earth for grain protection are: the amount used, kind of grain, the type of insect challenged, moisture levels in the grain, relative humidity, temperature, and length of storage. The kind of grain is important because diatomite does not adhere as well to corn as it does to other grains. There may also be qualitative factors such as insect preferences. When determining effectiveness, important factors are amount of repellency and its duration, toxicity to insects and its duration, and amount of grain damaged. Many of these questions were answered during large-scale field studies of sorghum, corn, and wheat stored for long periods in small bins (La Hue 1966, 1967a, 1967b, 1970, 1972, 1978).

Table 1. Insects on Treated and Untreated Wheat*

Substance in ppm	$% Protection after 6 mo.	%Protection after 12 mo.	% Kernels Damaged 15 mo.
Perma-Guard 2000	99.3	94.7	10
Perma-Guard 3500	99.4	96.3	6
Perma-Guard 5000	99.9	98.1	5
Cab-O-Sil	93.7	34.2	59
Cab-O-Sil 500	98.4	41.3	52
Cab-O-Sil 750	99.4	81.8	38
Malathion	92.2	71.3	30
Control	0	0	92

*%Protection = No. Insects in controls = No. insects in Treated/ No. in Controls x 100.

Table 1 shows the results of repellency and damage assays performed on the stored wheat. Repellency was assayed by counting the total number of insects in either treated or untreated bins. Small numbers of insects mean large repellency or a large percent protection. After y months both silica gel and diatoms protected grain better than malathion. At 12 months, even the lowest concentration level of Perma-Guard gave dramatically better protection than malathion. Although this test seems to measure pure repellency, La Hue was more cautious and believed, "the comparatively small number of live insects in wheat treated with the diatomaceous earths throughout the storage may have been a result of killing action, of repellency, or a combination of both." Grain damage after 15 months was 5 to 10% with diatoms and 305 with malathion (LaHue 1967a).

Diatoms on Dry Grain

When moisture content of the grain is low (e.g. 9.25%), and large enough concentrations of diatomaceous earth are used, stored products are protected better with diatomite than with a standard malathion treatment. Table 1 compares treatment with diatomaceous earth at 2000, 3500, and 5000 ppm with silica gel treatment at 250, 500, and 750 ppm and a standard malathion treatment of 1 pint 57% concentrate (0.63 lb. A.l.) per 1000 bushels. Tests were done in small (4 bushel) bins. Over a period of about six months there were five releases of about 15,000 stored product insects including: rice weevils, Sitophilus oryzae, confused flour beetles, Tribolium confusum; red flour beetles. T. castaneum; flat grain beetles, Cryptolestes pusillus; and saw-toothed grain beetles, Oryzaephilus surinamensis. The moisture content of the grain slowly increased during the year of the test from about 9% initially to about 13% at 12 months because storage was in open bins at about 50% relative humidity. Two kinds of diatomaceous earth, Kenite® and Perma-Guard® were actually used, but there was little difference between them. Each of the two silica gels, Cab-O-Sil® and Dri-die® SG-68 also gave similar results.

As can be seen from Table 1, silica gel did not protect as well as diatomaceous earth. Larger concentrations (750 ppm) though, obviously gave much better protection. In a later experiment La Hue (1970) showed that Cab-O-Sil at 1000 ppm was capable of giving slightly better protection to wheat (11.7% moisture) than either malathion or diatomaceous earth against the lesser grain borer, Thnyzopertha dominica. The diatomaceous earth was applied at 3500 ppm and the malathion treatment was a standard application of emulsion at 0.63 lb. a.1/1000 bushels. Grain was almost completely protected from insect damage for 12 months.

Mortality and Time

Table 2. Mortalities from Malathion or Diatoms*

Substance	Insect	Mortality 6 mo. %	Mortality 12 mo. %
P. Guard 2000	adult rice weevil	100.0	57.4
P. Guard 5000	adult rice weevil	100.0	92.9
Malathion	adult rice weevil	99.6	72.9
P. Guard 2000	c. flour beetle	93.6	39.2
P. Guard 5000	c. flour beetle	100.0	99.6
Malathion	c. flour beetle	65.4	8.8
P. Guard 5000	lesser g. borer	93.2	92.0
Malathion	lesser g. borer	99.6	59.6

*Mortality was assayed after a 21 day continuous exposure

As well as repellency and total amount of grain damage, toxicity as a function of time is also an important variable. In this study of dry (9.25% moisture) stored wheat, grain samples from the bins were taken at various times throughout 12 months and live stored grain insect species were added to test mortality from the treated grain during a continuous 21-day exposure. As seen in Table 2, Perma-Guard at the highest concentration gave better 12-month protection than malathion for all insects tested. Diatoms were more effective against the rice weevil than the lesser grain borer or the confused flour beetle. Malathion gave the poorest protection against the confused flour beetle. Clearly, all insecticides were less toxic at longer storage times. Toxic effects drop off with time due to physical and chemical changes that occur when the dust is exposed to the atmosphere in a thin film (Ebeling 1973).

Type of Stored Product Insect

Carlson and Ball (1962) also used Perma-Guard to protect wheat against several different insect species. Wheat at either 12 or 14% moisture was treated with 0 to 7000 ppm of diatomaceous earth. Mortality of the insects (% that died) was assessed after two weeks of continuous exposure. The lesser grain borer, rice weevil, granary weevil, and saw-toothed grain beetle all had much greater mortality at the lower moisture level. In fact, 2% less moisture often meant 30% greater mortality. The treatment was most effective for hairy insects such as the flat grain beetle, rice weevil, and granary weevil, Sitophillus granarius; somewhat less effective for saw-toothed grain beetle, khapra beetle larvae, Trogoderma parabile; and lesser grain borer, Rhyzopertha dominica. Mortality rates were lowest for smooth-surfaced insects such as the confused flour beetle, and red flour beetle. At the highest rates of application (7000 ppm) and the low moisture, mortality was 90% or better for all insects except Trogoderma larvae (58%), confused flour beetle (5.6), and red flour beetle (12.8%).

Mortality of confused flour beetle was very low in this experiment, but as we have seen in Table 2, La Hue observed high mortalities (nearly 100% at one year with 5000 ppm Perma-Guard) over long periods of time when the confused flour beetle was challenged with treated grain. One difference was that La Hue exposed the insects to treated grain for three weeks instead of two before assaying for mortality. More importantly though, the grain he used was drier at the start of the experiment. Initial grain moisture, then, is more important than the type of insect, and may be the most important factor in determining successful control of stored product insects with any particular diatomaceous earth or silica gel. The DE becomes ineffective in a moist environment, not because water fouls or saturates the absorptive surface, but because insects can constantly replenish their water loss by eating the moist grain.

Table 3. Influence of Moisture on DE Repellency

Crop	Treatment in ppm	Initial % Moisture	% Protection in 6 mo.	% Protection in 12 mo.	Reference:
wheat	2000	9.25	99.4	94.1	La Hue 1967a
wheat	3500	9.25	99.4	96.3	La Hue 1967a
wheat	5000	9.25	99.9	98.1	La Hue 1967a
wheat**	500	11.2	86.9	-	La Hue 1978
wheat	2727	13.0	Effective	Ineffective	Strong & Shur 1963
wheat	3636	13.0	Effective	Effective	Ibid.
sorghum	1895	13.0	Less than 0	Less than 0	La Hue 1967b
corn	2151	13.4	Zero	Less than 0	La Hue 1966

Effect of Moisture

As we see in Table 3, the initial moisture of the stored grain and the amount of diatomite used are two important factors in duration of protection. Diatomaceous earth was least effective for moist sorghum and moist corn. In both these cases, the initial grain moisture was more important than the relative humidity of the storage room. For the case of moist corn or sorghum, even when moisture decreased with time in dry storage, little protection was afforded. We also see from the Table 3 that even when the grain is somewhat moist, the effects of this can sometimes be overcome by the use of larger amounts of diatomaceous earth (DE).

The corn started out with a high (13.4%) moisture content, but was stored in a low humidity atmosphere. Because of the low humidity "marked reductions occurred in the moisture content of the corn during the first 3 months of storage." The toxicity of the diatomaceous earth increased as the grain moisture decreased, but after one year about 42% of the treated corn kernels had been attacked, versus about 90% damage to untreated corn. The concentration of diatomaceous earth used (2151 ppm) was not large enough to overcome the large initial grain moisture despite a favorable low humidity storage (La Hue 1966).

In general, mortality showed the same kind of decline with time seen with the repellency of the treated grain. In a toxicity test at one month, diatomaceous earth on corn killed 83.8% of the rice weevils, but was not very effective after this time. Few confused flour beetles were killed. After one month, the treated sorghum was largely ineffective against all insects tested in 21-day mortality tests. At one year the sorghum had been mostly destroyed by weevils. More weevils were in treated bins than controls because untreated grain had been eaten (La Hue 1967b).

Initial Infestation and Adherency

The situation for sorghum and corn was complicated by two other important variables - prior infestation and amount of adherency by the dust. The sorghum was infested with insects before it was treated, and DE does not adhere well to corn. Protection was a little better for corn, although the level of treatment was about the same as for sorghum, and the initial moisture levels were similar. Initial infestation is important because much of DE grain protection comes from repellency, and the most resistant beetles, such as the confused flour beetle, thrive on damaged grain. (Arbogast and Mullen 1988).

When applied to corn, the DE did not adhere well to the grains, and accumulated in the bottom of the bins, so the upper layers were protected less well than lower layers. A later study verified that diatomaceous earth does not adhere as well to corn as it does the wheat or sorghum (La Hue 1972).

Choice versus No Choice

In most of La Hue's experiments there was an excess of food available for the weevils released in storage bins. The experimental set was thus choice tests - insects had a choice of treated or untreated grain. When an infestation is severe, and little food is available, the test situation is essentially a no choice situation, and hungry insects must eat treated grain. For example, when small amounts (2kg) of wheat (13% moisture) were treated with diatomaceous earth at 1818 ppm, and 3636 ppm, the minimum of about 2000 ppm that La Hue found was adequate to protect the grain no longer worked for long storage times. All rates of application worked equally well for 6 months, but differences started to show at 9 months. Only the 3636 ppm treatment was effective for a full 12 months (Strong and Shur 1963).

USDA Storage Review

Other experiments have also shown that diatomaceous earth protects stored products better than malathian. Large quantities of grain can be protected for up to three years. Dust concentration can be lower when storage is at higher temperatures. The type of silica gel or diatomite used seems to matter in some cases. Due to space constraints, this material will be reviewed in a future paper on silica gel (White et al. 1975; White et al. 1966, Quinlan et al. 1966; Redlinger et al. 1966; USDA 1967; La Hue 1978).

Advantages and Disadvantages

The advantage of diatomaceous earth treatment for stored products is that it is non-toxic, is easy to separate from grain merely by washing it, and could possibly be recycled in storage bins. Small amounts can also be safely protected. Beans stored in 100 lb. sacks can be protected by as little as 300ppm. Or one-half ounce (Allen 1972). About 1 cupful (625 ppm) of Perma-Guard per 25 lbs. Of grain is recommended by Universal Diatoms. With stored wheat, the plumpness, moisture content and other characteristics of the kernels, and the baking characteristics of the flour are unchanged by treatment (La Hue 1967a). Freshwater diatomaceous earth is so non-toxic that there are no established tolerance levels for residues on grain. On the other hand, silica gel is rated as a "foreign substance" by the USDA. Even though silica gel is more effective on a weight basis than diatomaceous earth, its use results in lower quality grading upon inspection by the USDA. Any wheat containing silica gel is automatically given the lowest grade - "sample grade."

The disadvantage of diatomaceous earth treatment is that it reduces the weight per bushel of the treated product. This weight loss for dry wheat is about 4 lbs. Per bushel (a bushel weighs about 60 lbs.). The loss of weight is not due to water loss, but to a decreased bulk density of the treated grain. The dust adhering to the kernels affects the nestling and settling qualities of the grain, and it does pack as tightly. The problem is that weight loss per bushel is a USDA grading standard for determining grain damage from insects. Loss of weight per bushel means that the wheat is given a lower quality rating even if the total mass of the wheat is the same as it was before storage (La Hue 1967a).

Both dusts are superior to malathian in that they do not leave toxic residues, and their protective qualities arise mainly from repellency. Malathion does not repel insects, but protects by killing them. The dusts exert less Darwinian selective pressure, and thus there is less chance for resistance to occur.

Mode of Action

A continuing controversy concerning the use of inert dusts is their mode of insecticidal action. Various theories have been proposed, but the consensus now seems to be that all the dusts kill not by poisoning or suffocation, but by desiccation. The outer wax or grease layer on the insect is lost to the dust either through abrasion or absorption. Since the insect then has no protection against water loss, desiccation occurs and the insect dies. For instance, when stored product insects were rolled in Perma-Guard for 10 seconds, then held in a dry environment for 24 hours, the treated lesser grain borer had twice the water loss of control insects and dies 3 times faster; the same result was shown for the red flour beetle. The confused flour beetle had a water loss of about 61%, and death was faster than controls (Carlson and Ball 1962). Ebeling (1971) found that "regardless of the period required to kill an insect species, death occurred when 28 to 35% of the body weight (about 60% of the water content) was lost."

From La Hue's (1970) work we have seen that dry wheat can be protected about as well by treatment with 1000 ppm of Cab-O-Sil silica gel as by 3500 ppm Perma-Guard freshwater diatomaceous earth. For this application then, silica gel is about 3.5 times more effective by weight than diatomaceous earth. Part of the difference is due to adherence. About 73% of Perma-Guard applied at 3500 ppm to wheat adheres, whereas about 94% of the silica gel applied at 1000 ppm does. When the ratio is recomputed correcting for adherence, we find that silica gel is actually about 2.7 times more effective than diatoms (La Hue). La Hue did not publish the oil absorption capacity of the materials he used. A contemporary freshwater diatomaceous earth (Diafil) will absorb about 112-116% of its weight in oil (DiaFil 1992). The amount of oil taken up by diatomaceous earth was also measured on several German samples. The samples absorbed from 112 to 170% of their weight of peanut oil (Krezil and Wejroch 1936).

According to Harry Katz (1991a), "silica gel can hold oil up to 300% of its weight. Fresh water diatoms can hold up to 114% of their weight in oil." If only oil absorption were important, we would expect silica gel to be about 2.6 times more effective than diatomaceous earth. As oil absorption capacity seems to be a good predictor of effectiveness in this case, the absorptive power of the diatomaceous earth seems to be more important than its abrasiveness, at least for the insects and conditions tested by La Hue (1970).

Dryacide

Silica gel is not useful for the treatment of stored products because its small particle size makes it difficult to use. It is also rated as a foreign substance when grain is graded. These disadvantages are overcome by the use of a patented process whereby diatomaceous earth is coated with silica aerogels. The silica gel coating is 0.1% (w/ w) the treated particles range from 20 to 50 /u and the product has a packed bulk density of 15 to 100 lb./ft ^{3}

(Hedges and Bedford 1975). Dryacide is a gray dust that is 86% amorphous silica, 2% moisture, 8% clay, and 4% carbon from organic material in the original diatomite (Aldryhim 1990) (Since absorption power is increased by silica gel, a diatomite of lower purity can be used.)

Tests of Dryacide for stored product protection found that populations of the rice weevil, lesser grain borer, and red flour beetle showed 100% mortality with use of 1000 ppm at 65% relative humidity and 20 degrees C. Mortality rates declined with increasing humidity. Dryacide treated wheat also prevented the adult development of almond moth, Ephestia cautella eggs.

The 1000 ppm of Dryacide (1 g/kg) was easily removed either by washing or milling. Washed wheat contained less than 20 mg/kg, and milled flour from unwashed wheat contained less than 30 mg/kg. Residues larger than 100 mg/kg affect the quality of the wheat, including baking characteristics of the flour (Desmarchelier and Dines 1987).

Further Tests

Further tests were conducted on the granary weevil and the confused flour beetle at two different temperatures (20 and 30 degrees C) and two different relative humidities (40 and 60%). Dryacide was more toxic at lower relative humidities. The LC50 at 7 days for both species was less than 250 ppm at 40% R.H. regardless of temperature. At 60% R.H. the LC50 ranged from about 260 to 425 ppm. Toxicity measured at 2 days was 2.4 to 3.5 greater at lower relative humidities.

GARDENS AND FIELDS

Very few controlled studies of diatomaceous earth use in fields and gardens have been conducted. Even in these studies such basic information as the type of DE used is often omitted. In one field experiment diatomaceous earth (type and amount used not specified) was used as a physical barrier against the cabbage maggot, Delia radicum, in order to protect broccoli and Chinese cabbage. The treatment gave no protection, but it was applied late due to heavy rains, and had to be reapplied for the same reason (Matthews-G. and H. Goldstein 1988).

Application of diatomaceous earth (infusorial earth, probably marine DE) to corn fields reduced corn borer, Ostrinia (Pyausta) nubialis, populations by 50%. Unfortunately, corn yields were reduced by the same amount, apparently because silking was delayed by the treatment (Polvika 1931).

Mixtures of Derris (rotenone) and diatomaceous earth, or cryolite (Na3 AIF6) and diatomaceous earth were used to successfully treat beans and cabbage in field experiments against Mexican bean beetle (Turner 1946).

A controlled study in 1943 found diatomite successfully reduced pea weevil populations (86% mortality). California cotton treated with DE had greater yields than fields treated with insecticide, but part of this effect may have been due to key fertilizer elements such as magnesium that are present in diatomaceous earth (Tucker 1978).

Researchers at the University of Kansas Agricultural Experiment Station found that diatomaceous earth sprays were not very effective against cabbage looper, Trichoplasia ni, but that powder did somewhat better. Hen a pyrethrin-treated (0.2%) product equivalent to Diacide Homeguard® was used, however, cabbage looper, aphids, asparagus beetles, harlequin bugs and other insects was obtained. There were frequent applications because rain kept washing the DE away. The dust had very little effect on slugs (Wilbur et al. 1971).

Diatomaceous earth may be effective in controlling aphids, brown mites, red spider mites, twig borers, oriental fruit moths, and codling moths in orchards or chalcid weevils in alfalfa. The major problem with outside use, other than possible toxicity to beneficials is the nuisance value of the dust. Four applications of 700 bls/ac. may be necessary to maintain good control of chalcid weevils in alfalfa, for instance. The dust is extremely fine, and does not adhere well to foliage. It must be applied with an electrostatic applicator or shortly after plants have been moistened. Another reason diatomaceous earth may be impractical for field use is cost. When large areas are treated, it costs more than malathion. This disadvantage would not be a consideration for garden-size plots, of course (Ross 1981).

Under field conditions insects are repelled by diatomite dust applied to row crops and orchards. Although bees tend to avoid treated blossoms, predators are killed by dust application. To minimize death of beneficials, diatomite should be applied late in the evening or at night.

Although few controlled studies have been done, reports of garden use range from negative to wildly enthusiastic. "Users claim Thai diatomaceous earth is deadly to gypsy moth, codling moth, pink boll weevil, lygus bug, twig borer, thrips, mite, earwig, cockroach, slugs, adult mosquitoes, snails, nematodes, flies, corn worm, tomato hornworm, mildew and on and one" (Allen 1972). Negative responses have been either that it does not work, or that it killed released beneficials, such as lady beetles.

One method for garden use is to spread DE on the ground in the spring, then till it into the soil. Supposedly, this controls mollusks and kills cucumber beetles, bean beetles, cabbage loopers, and tomato hornworms emerging from pupal stages. The repellency of the dust should be exploited through the use of barriers, when possible. Trees are protected by coating the ground around the tree base, painting the trunk with Tanglfoot®, and applying DE to the adhesive. This treatment reduces migration of Japanese beetle grubs and fruit fly maggots. As a snail barrier, a two-inch wide band a quarter-inch thick is spread around the area to be protected. The DE should be kept dry for best results (DeCosta 1978).

Diatomaceous earth can also be applied with a mechanical pump-type duster, or a humble applicator such as a plastic ketchup bottle. For small areas, Necessary Trading sells DE in a salt-shaker type of container. A dust mask and protective clothing should be worn when dust is applied. Another method is to add 1/4 lb. DE to a 5 gallon sprayer, then add a quart of warm water containing a teaspoon of flax soap, then top off with water and mix thoroughly. One part D in 3 to 5 parts of water has also been used. This mixture can be sprayed on trees and vegetation (DeCrosta 1979).

One thing is sure, though, diatoms are less effective in hot humid weather. Control is better in areas with low rainfall. In one orchard where rainfall is less than 5 inches per year, damage was limited to 2% twig borer damage, and 2% from oriental fruit fly (Allen 1972).

Though there is much anecdotal evidence that DE works for controlled garden pests, only one company has registered it with the EPA as an insecticide for use in the garden. It is usually sold in garden stores as a "horticultural helper." The pyrethrin-treated products, though registered for garden use, cannot be used for agricultural purposes (see Box B for registration information).

BOX B. REGISTRATION INFORMATION FOR DIATOMACEOUS EARTH

Organic Plus® is a freshwater DE with no added insecticide. It has EPA registration for home and garden use on ants, cockroaches, fleas, earwigs, silverfish, boxelder bugs, beetles, and other crawling insects. It is also registered for use against slugs.

Diacide Homeguard® is a freshwater DE with 0.2% pyrethins. It is registered for garden use in all states except California and New York.

Perma-Guard D-10® is a freshwater DE registered for stored product use.

Perma-Guard D-20® which has 0.2% pyrethrins, is registered for household use.

Perma-Guard D-21® which has 0.1 pyrethrins is registered for garden use.

Shellshock® is freshwater DE with added adhesive. It is registered for inside use against cockroaches and other crawling insects. No diatomaceous earth product is currently registered for agricultural use, although Diacide and Organic Plus are currently preparing the kind of studies necessary for this registration.

New and Old

Shellshock® overcomes the inherent repellency of diatomaceous earth by adding attractants. The original formulation was 66% fresh water diatomaceous earth with 34% attractants such as cane sugar, cornstarch, dextrin, molasses, and soybean mill feedings (Dunlap 1962). The new version of Shellshock has 855 DE and an improved adhesive (Dunlap 1992).

A non-toxic insecticide for flying and crawling insects was prepared from 90% Celite, 8% skim milk, and 2% yeast extract. A fast knockdown of houseflies and mosquitoes was observed after spraying with this material (Carle 1985).

An improved Dryacide for cockroach control has also been patented. Diatomaceous earth (302 grams) fine enough to sift through 200-400 mesh screen is treated with 400 grams of silica gel. The stabilized product is then mixed 1:1 (w:w) with powdered boric acid. When the product is spread at a rate of 2 g/m3, cockroaches are controlled within 7 hours (Belford 1990).

A heavy application of DE dust to cattle can control cattle lice, Bovicola bovis. This approach might have to be used again if the organism becomes resistant to current control agents (Matthysse 1946).

Household Use

Diatomaceous earth and silica gel are both useful for pest management in dwellings. Cockroaches are especially sensitive to these kinds of desiccants, which is fortunate as they are becoming resistant to chemical pesticides. In a field test in Georgia, diatomaceous earth with pyrethrins (Diatect® - 0.2% pyrethrins, 1% PBO, DE 88%) was tested along with silica gel (DriDie® - 95.3% silica gel, 4.7% ammonium fluosilicate), and silica gel with pyrethrins (Drione® - 30% silica gel, 1.0% pyrethrins, 10% PBO, and 49% petroleum distillates). Boric acid, bendiocarb, diazinon, and chlorpyrifos were also tested in the same experiment.

Dusts were applied with a .2kg Centrobulb duster (Central Robber Prod., South Salem, NY 10590). Heavy infestations (kitchens with more than 25 cockroaches visually sighted) in 40 homes were treated. Effectiveness data were determined after one treatment at roach hot spots in the kitchen. (Near or behind refrigerators greatest, wall cabinets next, floor cabinets least.) One application of pesticide was applied, then cockroaches were monitored by traps at 1, 2, 4, and 8 weeks.

Cockroach populations were reduced by all treatments. The treated diatomaceous earth did not do as well as the other products. "Boric acid, chlorpyrifos, Drione, and Dri-Die did not offer in efficacy while all four produced greater mortality than bendiocarb, diazinon and Diatect." However, the time spectrum was slightly different among the most effective products.

Chlorpyrifos and Drione brought about the quickest reduction in populations, 93 and 96%, respectively, after the first week. The effectiveness of the silica products dropped off somewhat with time. At 8 weeks DriDie showed a 54% reduction in population (initially 79%), and Drione showed a 78% reduction at 8 weeks compared to 96% at week one. The boric acid started off slowly, then improved in effectiveness with time. In the first week the reduction was 69%, but in weeks 2 through 8, reduction was constantly above 90%. Boric acid gave the greatest overall control throughout the test (Wright and Dupree 1984).

A similar test compared Diacide® to Diacide with 0.2% pyrethrins and to Drione® for German cockroach control in kitchens and bathrooms of infested urban apartments in Virginia. Dusts were applied to cracks and crevices, wall voids, and inaccessible areas behind refrigerators and stoves. Sticky trap counts to monitor success were made `, 1, 2, and 4 weeks after the test and compared with similar counts made before treatment. The insecticides with pyrethrins worked quicker, but there was no significant difference between the products when results were monitored over four weeks (Rambo 1992).

When food and water is available, roach mortality is delayed. For instance, German cockroach populations exposed to 1 g/ft.2 of shellshock have 100% mortality in 24 hours when confined without food or water. When food and water is provided, 100% mortality takes 15 days. (Less than 20% of the controls are dead at this time.) The roaches' normal behavior is disrupted, however, and thirsty roaches spent 40% of their time at water sources, compared to 0.9% for controls. American, Oriental, and brownbanded cockroaches take 5 or 6 days for 100% mortality without food or water, and 13 to 18 days when water is available (Snetsinger 1988).

Another problem is the diatomaceous earth repels roaches. Consequently, they are often flushed from treated areas, but not killed. One strategy is to treat cockroach harborage with diatomaceous earth to deny the insects a comfortable home, then kill those that are flushed out with a knockdown insecticide such as pyrethrins (Ebeling 1971; Katz 1991b).

Another approach is to modify application methods or the product to reduce repellency. For instance, repellency is reduced if applied concentration is kept below 3 oz per 100 ft.2 (Katz 1991a). Attractants can also reduce repellency. Dorsey Dunlap's original DE insecticide contained molasses and sugar. His Shellshock does not repel American cockroaches exposed to a surface dusting of 2g/ft.2. Also, since Shellshock contains no toxic ingredients, its use in meat packing plants has been recently approved (Snetsinger 1992).

Safety of Diatomaceous Earth

Ingestion of diatomaceous earth is not toxic to mammals. Rats fed a daily diet containing 5% freshwater diatomaceous earth show no abnormalities after 90 days (Bertke 1964). Dairy farms sometimes feed their animals food containing 1 to 2% diatomaceous earth to control worms and other internal parasites (Allen 1972). Impoverished humans add "fossil flour" to their baked goods in order to stretch their flour supply (Cummins 1975). It is so safe for use on food that the FDA has exempted diatomaceous earth from requirements of fixed residue levels when added to stored grain (Fed. Reg. 1961). The U.S. EPA also allows its use in food storage and processing areas (Fed. Reg. 1981).

The only possible health effect comes from long-term chronic exposure to quantities of the inhaled dust. Current maximum U.S. exposure standards are 6 mg/m2 of dust containing less than 1% crystalline silica (Pestline 1991). Calcined diatomaceous earth poses the greatest problem. For instance, rats showed little reaction when their lungs were exposed to 5-80 mg of naturally occurring diatomaceous earth, but a strong reaction to diatomaceous earth than had been calcined (heated to 800 degrees C) (Swenson 1971), Japanese workers chronically exposed to diatomaceous earth showed significant serum increases of the protease enzymes that correlate with emphysema (Omura 1981). Marine diatomaceous earth has enough crystalline silica in it that mining can cause health problems. Diatomite from this source may produce a distinct type of pneumoconiosis, the term applied to any abnormality in the lungs resulting from the inhalation of dust (Abrams 1954).

ACKNOWLEDGEMENT

The author wishes to thank Dr. Walter Ebeling for comments on the manuscript.

RESOURCES:

Shellshock - Dorsey, Inc.	136 Elm Street, South Williamsport, PA 17701. Tel: (717) 322-4885.
Diacide - Diacide, Inc.	1068 H Avenue, Nevada, Iowa 50201. Tel. (800) 767-6222.
Organic Plus -	Organic Plus, 1024 First Street NW, Albuquerque, NM 87102. Tel. (800) 933-2278, (505) 242-5558
Perma-Guard -	Universal Diatoms, 3434B Vassar NE, Albuquerque, NM 87107 Tel. (505) 881-6933
Pristine Products -	2311 E. Indian School Rd., Phoenix, AZ 85016 Tel. (602) 955-7031
Harmony Farm Supply -	P. O. Box 460, Graton, CA 95444 Tel. (707) 823-1734
Necessary Trading -	8311 Salem Ave., New Castle, VA 24127 Tel. (800) 447-5354

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