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Naphthalene
as a
Greenhouse Fumigant

By W. D. Whitcomb

Naphthalene fumes may be used to kill certain greenhouse pests, particularly the common red spider, which are not controlled by the standard fumigating materials containing nicotine or hydrocyanic acid gas. This bulletin is intended to supply specific information regarding the conditions under which greenhouse fumigation with naphthalene is both safe and effective.

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NAPHTHALENE AS A GREENHOUSE FUMIGANT

By W. D. Whitcomb, Research Professor of Entomology

INTRODUCTION

In a greenhouse where confined gases will penetrate all available areas and where they can be discharged with a reasonable amount of labor and expense, fumigation is the ideal method of pest control. Unfortunately, however, the standard fumigating materials containing nicotine and hydrocyanic acid gas, which satisfactorily control the majority of greenhouse insect pests, do not effectively control the common red spider at concentrations and exposures which can be safely used on most greenhouse plants. Naphthalene fumes have a specific toxic action on the common red spider and other pests; and when certain factors such as temperature, relative humidity, dosage, and length of exposure are controlled, fumigation with naphthalene is a safe and effective treatment on many species of greenhouse plants.

DESCRIPTION OF NAPHTHALENE

Naphthalene is an organic chemical compound having the symbol $C_{10}H_8$ and is produced by the destructive distillation of coal. When pure it forms flat colorless crystals having a penetrating but not unpleasant odor and a burning aromatic taste. The fumes are irritating to the eyes, usually inducing tears, but reasonable exposure to them is not harmful. Naphthalene melts at $80.1^{\circ}C.$ ($176.2^{\circ}F.$) and boils at $217.9^{\circ}C.$ ($424.2^{\circ}F.$). The crystals volatilize slowly at about $70^{\circ}F.$ and this action increases with the amount of water vapor in the air. They are insoluble in cold water but can be dissolved in ether, alcohol, and other organic solvents.

Naphthalene finds its greatest use in the dye industry where, in combination with other chemicals, it is used in the manufacture of various colors, especially red and yellow. It is prepared for commerce in a crude form (bags) both domestic and imported, flake form (barrels), dyestuff (bags), and as the well-known moth balls (barrels) where it may be combined with camphor. The retail price for the commercial forms ranges from 8 to 12 cents a pound. A resublimed form (100 percent pure) is available in limited quantities at a considerably greater cost.

Naphthalene which is to be used for fumigating living plants should be approximately 95 percent pure. The principal impurities are forms of unrefined coal tar, the fumes of which are injurious to plant life. Crude naphthalene, which is the cheapest commercial grade, contains variable quantities of these impurities and its analysis is neither guaranteed nor constant. Resublimed naphthalene is the purest form which is commercially available and was used in the first work with this material for greenhouse fumigation. Commercial flake naphthalene is a very nearly pure product which has been found entirely satisfactory for fumigating, and this form was used in the experiments reported herein.

HISTORY OF NAPHTHALENE AS AN INSECTICIDE AND INSECT REPELLENT

On Field Crops

Twenty or more years ago, naphthalene was more generally used for preventing insect damage on trees, vines, and vegetables in Europe than in America. According to Bourcart (4) at least a dozen mixtures included naphthalene in their formulas and their uses were widespread. In the sprays, washes, and dips, the naphthalene was generally combined with coal tar and lime, while some form of sulfur or copper was occasionally added. Some of the materials of this nature which were frequently used were known as Crouzel's Anticryptogamic, Balbiani's Ointment, Occidine, and Rathay Bouillie. Solutions of naphthalene, 1 part in 8 parts of alcohol or benzene (1 pound in a gallon), were also used. Dusts for the treatment of growing plants were prepared by mixing naphthalene with sulfur, pyrethrum, lime, or ashes. For killing and repelling soil insects such as wireworms, naphthalene was mixed with sand or with sawdust and sown with the seed or worked into the soil with the manure. More recent literature indicates that naphthalene is less popular, probably because it has been supplanted by more effective materials.

In the United States, one of the oldest remedies for preventing injury to stored clothing, wool, fur, and leather by clothes moths or carpet beetles is storing them with naphthalene. Back (1, 2) recommends 1 pound in each 10 cubic feet for this purpose. To control fleas in a building, Bishopp (3) recommends using 5 pounds in each ordinary sized room.

More recently, a wash prepared with soap, naphthalene, flour, and water for painting the trunks of trees to prevent oviposition by the flat-headed apple tree borer has been recommended in Michigan (11). A somewhat similar emulsion of naphthalene and cottonseed oil was used by Snapp (15) in Georgia for peach borer control with somewhat unsatisfactory results.

The carrot rust fly was effectively controlled by Glasgow (5) by broadcasting 6 applications of crude naphthalene at the rate of 400 pounds per acre, and Maughan (9) in New York used it quite successfully to control onion thrips in the field. The experiments of Weigel et al. (20) have shown that naphthalene when stored with gladiolus corms provides a very effective and practical control of the gladiolus thrips.

The larvae, pupae, and eggs of the Japanese beetle are killed by thoroughly mixing the soil with naphthalene flakes (19). When used at the rate of 5 pounds for each cubic yard for potting soil, and 1,000 pounds per acre or 23 pounds per 1,000 square feet in cold frames, hotbeds, or nursery rows, naphthalene constitutes an approved treatment for disinfecting the soil of this pest.

It appears that the use of this material for insecticidal purposes is now increasing in this country.

On Greenhouse Crops

Among the first records of the use of naphthalene as a greenhouse fumigant are those discussed in the reports of the Experimental and Research Station, Cheshunt, Herts, England. Here, Speyer (16) in 1923, after preliminary laboratory work with a large number of volatile liquids and volatile solids dissolved in liquids, found sufficient encouragement in white flake naphthalene to use it on a practical scale. At first, the naphthalene was dissolved in tetrachlorethane, this solution being poured on the ground and on the steam pipes

with variable results. Later, flakes were mixed with sulfur and spread on the steam pipes with more satisfactory results.

In 1924, broadcasting the naphthalene along the walks of the greenhouse (17) became the approved method of application, using from 2 to 12 pounds in each greenhouse 100 feet long. Continued studies showed that exposures of about 72 hours were advisable and that air temperatures above 74° F. with high relative humidities were preferable. In 1925, the normal dosage was placed at 6 pounds in each 100-foot greenhouse, and a standardized grade of naphthalene known as "Grade 16" which would pass through a screen containing 16 meshes to the inch was prepared especially for fumigating. Practically all of this work was the result of efforts to find more effective methods for combating the common red spider¹ on greenhouse cucumbers, and apparently this treatment became well established in England.

This special grade was evidently the first form of naphthalene to be prepared commercially strictly for fumigating purposes, being handled by Geo. Munro, Ltd., who supplied many tons to the cucumber growers in the Lea Valley section about 1925.

About 1926 Hartzell (6) and the author began experimenting with naphthalene as a greenhouse fumigant, and the encouraging results of the preliminary work led several florists in the northeastern United States to fumigate with this material on a practical scale. This work also led to the manufacture and distribution in 1928 by the Fuller System, Inc., Woburn, Massachusetts, of the first commercial naphthalene fumigant to be available in this part of the country. In February, 1932, a patent (U. S. 1,845,977) was issued on this material and methods for its use in greenhouses. This patent apparently covers only the manufacture and use of mixtures composed of naphthalene and other coal tar derivatives rather than naphthalene alone, since the application was not filed until more than four years after the publication of the reports of Speyer (16), Parker (10), and Hartzell (6).

About 1930, mixtures containing naphthalene and ground tobacco stems were prepared and used extensively for combating soil inhabiting pests in greenhouse beds and benches. These materials when spread on or mixed with the surface soil were quite effective for eliminating earthworms, snails, sow bugs, and similar soil inhabiting animals, but were not entirely satisfactory for combating pests on the aerial parts of plants.

EQUIPMENT FOR FUMIGATING WITH NAPHTHALENE

The application of artificial heat in some form to control the rapidity with which naphthalene is vaporized is the common method of using this material for greenhouse fumigation in Massachusetts. Many lamps and stoves have been devised for this purpose. Most of these devices supply sufficient heat to melt the naphthalene and maintain it in a liquid condition without boiling, while others increase and control vaporization by circulating warm air over crystallized naphthalene.

Parker (10) used a paraffin lamp over which an inverted cone supporting a pan containing the naphthalene was suspended. Hartzell (6) surrounded an ordinary house lamp with a ventilated sheet iron cone to support the pan of naphthalene. Some growers varied this by substituting a sheet iron chimney with a mica door for the glass chimney on a house lamp. The Fuller System,

¹*Tetranychus telarius* L.

Inc., manufactured a two-wick oil stove with a sheet iron chimney and pan support. Some growers used Union oil stoves with satisfactory results. The rapidity of vaporization in these stoves is controlled by adjusting the height of the flame.

Hartzell (7) used a three-heat electric hot plate on which was placed a porcelain or sheet iron dish to hold the material, and the writer varied this by constructing a frame over the hot plate which would hold the dish at various heights above the heating unit in order to regulate the amount of naphthalene volatilized in a given time. Hartzell and Wilcoxon (8) developed a naphthalene saturator in which the greenhouse air was blown over large quantities of naphthalene balls for 8 to 15 hours, the concentration of the fumes being governed by the length of time the saturator was in operation. The writer has extended this idea by devising an electric naphthalene fumigator in which the air is heated to about 165° F. (just below the melting point of naphthalene) by passing it through a slowly revolving fan in front of which is placed a series of electrically heated resistance wires. This heated air circulates through a cabinet containing trays permitting exposure to the air of a large part of the crystals in them. The heated air speeds up the volatilization of the crystals and the concentration is governed by the amount of crystals in the trays and by the length of time the equipment is operated. As with the Hartzell and Wilcoxon saturator there is no danger of boiling or burning the naphthalene; good circulation of the fumes is provided by the fan, and many of the more susceptible plants which have suffered injury when fumigated by the lamp method have been treated safely with this equipment.

In 1933, the Hartzell and Wilcoxon saturator (8) was improved to use liquid solutions containing naphthalene. In this apparatus a solution containing a known quantity of naphthalene dissolved in a light motor oil was pumped over a cone in such a way that the air became charged with naphthalene as it was forced through the solution falling from the cone. The amount of naphthalene in the solution governed the concentration of the naphthalene vapor in the air.

In the average greenhouse the most practical equipment appears to be the two-wick oil stove as shown in Plate I.

Experimental Fumigation Chamber

The majority of the experiments at the Waltham Field Station were conducted in a specially constructed gas-tight chamber containing 1,500 cubic feet, located within a standard greenhouse section. This chamber is about 14 feet long and 10 feet wide with cement floor and side walls 2 feet high on which is constructed a greenhouse frame with 30 x 16 inch glass set in putty. The door and door frame are beveled and closed with a pressure slide latch. Circulation is maintained by an electric fan operated at slow speed. The naphthalene was vaporized over an electric hot plate as described above. A constant temperature was maintained by supplying heat from steam pipes, controlled by a thermostat operated by air pressure from an automatic compressor. Constant relative humidity was maintained by the operation of a horse-hair regulator supplied with 30 pounds air pressure controlling a spray of water from a nozzle delivering 8 gallons per hour. An electric fan operating in an exhaust opening with a hinged door enabled the fumes to be evacuated quickly when the fumigation was completed.

ACTION OF NAPHTHALENE FUMES

On Insects and Spiders in General

Reports by Speyer (16) and Hartzell (6) show that naphthalene has a selective toxicity to the common red spider and the greenhouse thrips (p. 19 footnote), and as a fumigant gives better control of red spider with safety to many plants than other known fumigants. Therefore, the experimental studies and the practical development of naphthalene fumigation have been based largely on its effectiveness as a control for the common red spider.

The toxicity of naphthalene to insects and spiders is apparently dependent upon a relatively long exposure in air containing naphthalene vapor. The action of these fumes on the insect is paralytic and the first evidence is shown by a lack of control of the legs and other appendages even though they can be moved freely. The cause of this action is not definitely known, although it appears that the gradual paralysis is due to the partial exclusion of oxygen from the respiratory system. With continued exposure paralysis increases until death results, and there is no evidence that the body tissues are burned or seared in any way. Four or five days after death the bodies of the fumigated insects and spiders collapse and dry.

The high temperature and high relative humidity which are necessary for successful naphthalene fumigation provide conditions tending to increase respiration and body metabolism in animals, thus aiding the penetration and toxic action of the naphthalene fumes. It is also apparent that naphthalene fumes penetrate the chorion of the egg and kill the embryo in the same way that the active stages are killed.

Early in the studies it was observed that the different stages of the red spider possessed a varying degree of resistance to fumigation, and experiments were therefore conducted with eggs, larvae, nymphs, and adults.

On Red Spider Eggs

In 1927, Read (12) reported that eggs were killed by an eight-hour exposure to a saturated atmosphere of naphthalene at 100° F., and that the time required to kill them decreased as the temperature and atmospheric moisture increased. However, this temperature is higher than can be maintained under practical conditions.

At Waltham newly laid eggs failed to hatch after two or more fumigations of six hours duration using 3 ounces of naphthalene per 1,000 cubic feet at 75° F., as shown in Table 1.

TABLE 1.—MORTALITY OF RED SPIDER EGGS ON CARNATION LEAVES AFTER FUMIGATION WITH NAPHTHALENE.

Temperature 75°F. Relative Humidity 80—90 percent. Exposure 6 hours.
Dosage 3 ounces per 1000 cubic feet.
Waltham, Massachusetts. April 1930.

Number of Fumigations	Number of Eggs	Percent Hatched
None	46	89.13
1	48	12.50
2	43	0
3	46	0
4	48	0

The age or degree of incubation of the eggs influences their susceptibility to fumigation, as shown in Table 2. In this experiment, eggs were divided into two groups: those which had become a deep straw color and showed the developing embryo within, and those which had been laid during the previous 24 hours. These eggs were placed in short glass tubes filled with plaster of Paris, which permitted a small amount of moisture to reach them when the tubes were set on damp sand (14). Since more than 80 percent of the unfumigated eggs hatched, these tubes apparently provided satisfactory conditions for incubation. Under these conditions, none of the older eggs hatched after one or more fumigations, while it required four fumigations to prevent all of the newly laid eggs from hatching. Fumigated eggs developed a slightly darker color than the untreated eggs, but this change in color was not always consistent and in many cases it was impossible to determine the effect of the treatment until long after the eggs should have hatched under natural conditions.

TABLE 2. — MORTALITY OF NEW AND OLD EGGS OF RED SPIDER AFTER FUMIGATION WITH NAPHTHALENE.

Dosage 3 ounces per 1,000 cubic feet.
 Temperature 80°F. Relative Humidity 90 percent. Exposure 6 hours.
 Waltham, Massachusetts. March 1930.

Number of Fumigations	Number of Eggs Observed	CONDITION OF EGGS AFTER TREATMENT							
		5 Days		10 Days		15 Days		20 Days	
		Dead	Hatched	Dead	Hatched	Dead	Hatched	Dead	Hatched
New Eggs									
None	20	1	2	2	13	3	16	4	16
1	10	0	0	4	1	6	1	9	1
2	10	6	1	7	1	8	1	9	1
3	10	4	0	6	1	6	1	9	1
4	10	7	0	10	0	-	-	-	-
Old Eggs									
None	20	2	10	3	17	-	-	-	-
1	10	4	0	4	0	8	0	10	0
2	10	3	0	6	0	7	0	10	0
3	10	3	0	3	0	7	0	10	0
4	10	4	0	6	0	7	0	10	0

On Active Stages of Red Spider

An examination of infested plants after fumigation which has resulted in an incomplete kill of common red spiders usually shows a predominance of larvae, second stage nymphs (deutonymphs), and adult males among the living spiders. The results summarized in Table 3 indicate that these forms have a slightly greater resistance to naphthalene fumigation than the first stage nymphs

(protonymphs) and the adult females. This may be partially explained in the case of deutonymphs by the fact that many of them at the time of fumigation are in the first or proto-quieting molting period of suppressed activity, when they are obviously less susceptible to toxic fumes. In the case of the adult males, it is apparent that they are the most active of all stages and are able to select most quickly any protective parts of the plant where the fumes penetrate with difficulty. Red spider larvae are quite easily killed by naphthalene fumes and those individuals which are so commonly present a few days after treatment have hatched from eggs which survived the exposure. It has also seemed very probable that many of the adult females which survive were in the second molting period during fumigation.

TABLE 3. — PERCENTAGE OF THE DIFFERENT ACTIVE STAGES OF COMMON RED SPIDER KILLED BY NAPHTHALENE FUMIGATION.

Dosage 3 ounces per 1,000 cubic feet.
 Temperature 80°F. Relative Humidity 95 percent. Exposure 6 hours.
 Waltham, Massachusetts. March 1930.

STAGE OF DEVELOPMENT	ONE FUMIGATION		TWO FUMIGATIONS	
	Number of Spiders	Mortality Percent	Number of Spiders	Mortality Percent
Larva	169	69.82	102	96.08
Protonymph	167	74.20	109	100.00
Deutonymph	41	53.68	74	100.00
Adult Male	33	33.33	4	100.00
Adult Female	44	72.50	48	100.00
Total	454	70.28	333	98.81

FACTORS INFLUENCING THE EFFECTIVENESS OF NAPHTHALENE FUMIGATION

Crystal naphthalene volatilizes slowly at any temperature suitable for growing plants, but a sufficiently rapid volatilization for controlled fumigation takes place only at temperatures near the melting point of the crystals (176.2°F), and the experiments reported herein are based almost entirely on the volatilization of melted naphthalene. In certain apparatus (p. 5) the naphthalene is volatilized by blowing over the crystals air at normal greenhouse temperatures or at moderately high temperatures, but these methods are effective only when the exposure is two or three times longer than if the naphthalene is melted.

Roark and Nelson (13) have calculated that the greatest amount of naphthalene vapor which can exist in 1,000 cubic feet of air at 77° F. is 0.04 pound (0.64 ounces or 18.14 grams) and that this constitutes saturation. The amount necessary for saturation increases slightly as the temperature and vapor pressure increase, becoming approximately 21 grams at 80° F. and 80 percent relative humidity.

Dosage

The maintenance of a sufficient concentration of naphthalene vapor for several hours is necessary for successful fumigation; and the correct amount of naphthalene crystals to be vaporized in a given cubical unit in order to

make and maintain that concentration varies with the leakage, adsorption, air drafts, temperature, and relative humidity. Therefore, any standard dose which is determined under experimental conditions may necessarily be varied when applied in actual practice in different greenhouses or under different conditions in the same greenhouse.

In a practically gas-tight fumigation chamber during a six-hour exposure 4 and 5 ounces of naphthalene per 1,000 cubic feet have been vaporized without causing noticeable injury to resistant plants such as carnations. However, the volatilization of such an excess above the computed saturation point causes supersaturation which can exist only for a short time [without recrystallization or other physical and chemical changes. In the experimental fumigation chamber 2 and 3 ounces per 1,000 cubic feet have frequently killed 95 to 100 percent of the common red spider in one 6-hour fumigation and have resulted in practically perfect control in two fumigations. With high relative humidity, 1½ ounces per 1,000 cubic feet was equally effective in two and three treatments, and occasionally in one treatment. A dosage of 1 ounce per 1,000 cubic feet was not consistently effective in less than three successive fumigations.

The effectiveness of these dosages is somewhat decreased under average greenhouse conditions, and the most satisfactory dosage under normal conditions is 2 to 3 ounces per 1,000 cubic feet.

Exposure

The effectiveness of naphthalene fumigation is determined by the length of time the red spiders are exposed to an atmosphere which is partially or completely saturated with naphthalene vapor. Wilcoxon et al. (21) have shown that satisfactory control of red spider resulted from an exposure of 14 to 16 hours to a 13 percent saturated atmosphere in one case, and an approximately one-half saturated atmosphere in another case, when unmelted naphthalene was vaporized in special equipment. However, when the naphthalene crystals are melted and complete saturation of the atmosphere is obtained, a 6-hour exposure is satisfactory.

As shown in Table 4, the vaporization of ¼ ounce of naphthalene each hour failed to have an appreciable effect on red spider until after 3 hours when ¾ ounce of naphthalene had been vaporized. At this time the concentration approached saturation, and thereafter the kill increased each hour until a mortality of 88 percent was obtained after 5 hours exposure. When the spiders were first exposed 2 hours after fumigation began, at which time ½ ounce of naphthalene per 1,000 cubic feet had been vaporized, a mortality of 85 percent was reached after an exposure of 4 hours, 3 hours of which were in a nearly saturated atmosphere. When red spiders were first exposed after the vaporization of ¾ ounce per 1,000 cubic feet in 3 hours had built up a calculated saturated atmosphere, an 85 percent kill resulted after 3 hours exposure. A mortality of 85 percent was also obtained in 3 hours when the spiders were first exposed after 1 ounce of naphthalene had been vaporized in 4 hours, since in both cases the air was approximately saturated when the spiders entered. However, a 2-hour exposure to saturated atmosphere in which 1 ounce of naphthalene had been vaporized killed 68 percent of the red spiders, but only 24 to 34 percent were killed by equal exposures to less saturated atmosphere in which ½ or ¾ ounce had been vaporized.

TABLE 4. — PROGRESSIVE MORTALITY OF COMMON RED SPIDER ON POTTED CARNATION PLANTS FUMIGATED WITH NAPHTHALENE

Naphthalene vaporized at rate of $\frac{1}{4}$ ounce per 1,000 cubic feet each hour.
 Temperature 75°F. Relatively Humidity 85 percent.
 Waltham, Massachusetts. October 1935.

Length of Time Fumigation Had Been in Progress when Plants were First Exposed	Total Naphthalene Vaporized when Plants Were Removed	PERCENTAGE MORTALITY OF RED SPIDER AFTER EXPOSURES OF —					
		1 Hour	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours
	Ounces						
At the beginning	$\frac{1}{4}$	14.19					
	$\frac{1}{2}$		20.32				
	$\frac{3}{4}$			32.78			
	1				52.00		
	$1\frac{1}{4}$					83.89	
	$1\frac{1}{2}$					94.36	
2 Hours	$\frac{3}{4}$	16.38					
	1		33.94				
	$1\frac{1}{4}$			55.20			
	$1\frac{1}{2}$				85.83		
3 Hours	1	19.39					
	$1\frac{1}{4}$		24.35				
	$1\frac{1}{2}$			84.68			
	$1\frac{3}{4}$				92.79		
4 Hours	$1\frac{1}{4}$	16.66					
	$1\frac{1}{2}$		68.75				
	$1\frac{3}{4}$			85.08			
	2				97.58		

NOTE: Percentage mortality of red spiders on plants not fumigated, 7.54.

From this experiment it is apparent that normal fumigations under favorable conditions do not give a reasonable control (85 percent dead) until the red spiders have been exposed for 3 hours or longer to an atmosphere in which at least $\frac{3}{4}$ ounce of naphthalene per 1,000 cubic feet has been vaporized and retained.

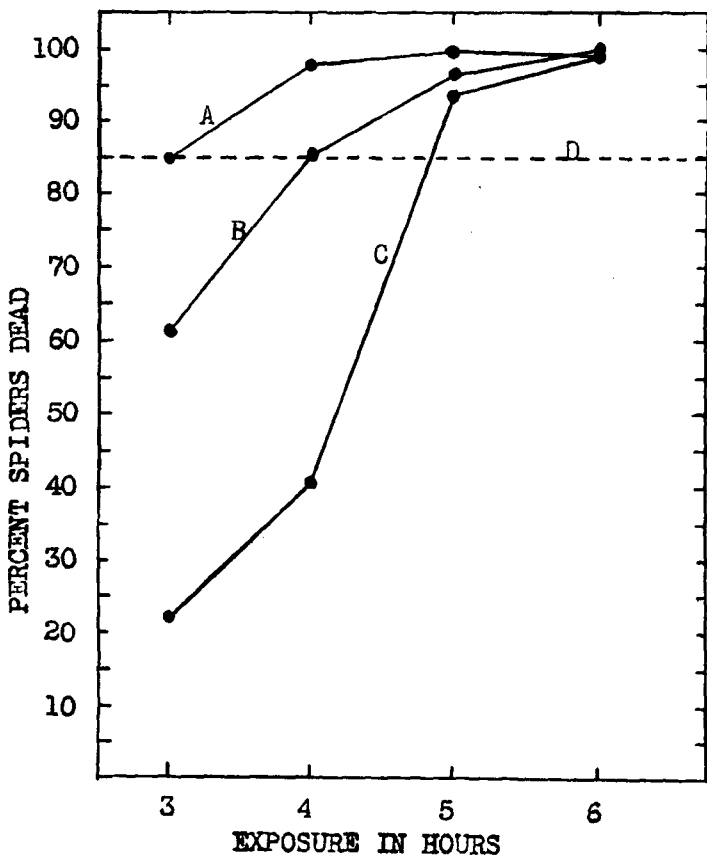
Similar results are indicated in Figure 1 where the time required to build up a calculated saturated atmosphere was decreased by increasing the rapidity with which a normal effective dosage for a 6-hour exposure was vaporized. In this experiment the vaporization of 3 ounces of naphthalene in 3 hours at the rate of 1 ounce each hour killed 85 percent of the red spiders in 3 hours; but at the rate of $\frac{3}{4}$ ounce each hour for 3 hours followed by $\frac{1}{4}$ ounce each hour for 3 hours, an exposure of 4 hours was required to kill 85 percent of the red spiders; and at the rate of $\frac{1}{2}$ ounce each hour for 6 hours, a 5-hour exposure was necessary to effect an equal mortality.

Manipulation of the fumigant in this way is practical only in extremely tight greenhouses under favorable conditions and with careful attention to detail by experienced operators.

Although experiments under ideal conditions in a special fumigation chamber indicate that an exposure of 3 to 5 hours is frequently effective, actual practice shows that the efficiency of naphthalene fumigations is usually less under average greenhouse conditions and an exposure of 6 hours is necessary.

Figure 1—Mortality of Common Red Spider When Naphthalene is Vaporized at a Heavy Uniform Rate during the First Half of the Exposure, and at a Light Uniform Rate, or Omitted, During the Last Half of the Exposure as Compared With a Uniform Vaporization During the Whole Fumigation.

Dosage 2 Ounces per 1,000 Cubic Feet. Exposure 6 Hours.
 Temperature 75° F. Relative Humidity 75 Percent.
 Waltham, Massachusetts. 1935.



- A — 1 ounce each hour for 3 hours — none for 3 hours
- B — $\frac{3}{4}$ ounce each hour for 3 hours — $\frac{1}{4}$ ounce each hour for 3 hours
- C — $\frac{1}{2}$ ounce each hour for 6 hours
- D — Commercially effective mortality from 1 fumigation

Interval Between Fumigations

Frequently, three or four successive fumigations within 10 to 15 days are required to give satisfactory control. When successive fumigations are necessary, the interval between treatments should not be longer than one week during which time the majority of the spiders will have hatched from eggs not killed by previous fumigations. In Table 5 the results of fumigations at intervals of one, two, and three days show a slight advantage where the fumigations were made on successive days. However, the mortality after two- and three-day intervals is high and the differences are insignificant. It is, therefore, apparent that within a reasonable period successive fumigations should be made when the weather conditions are most suitable rather than at any predetermined intervals.

TABLE 5. — MORTALITY OF COMMON RED SPIDER AFTER FUMIGATIONS WITH NAPHTHALENE AT INTERVALS OF 1, 2, AND 3 DAYS BETWEEN FUMIGATIONS.

Dosage 2 ounces per 1,000 cubic feet.
 Temperature 75°F. Relative Humidity 80 percent.
 Waltham, Massachusetts. March 1931.

MORTALITY OF RED SPIDERS, PERCENT			
Number of Fumigations	1 Day between Treat- ments	2 Days between Treat- ments	3 Days between Treat- ments
1	69.34	38.70	31.64
2	72.82	79.87	90.67
3	100.00	95.79	98.83
4	100.00	92.59	94.44
None (check)	25.25		

Count made 5 days after fumigation.

Operation and Number of Stoves

The uniform vaporization of naphthalene throughout the total period of exposure is necessary for successful operation, and this is governed by the amount of heat generated by the stove. In coal-oil stoves this depends on the height of the flame. In general, the flame should be about one-third high but the proper adjustment of the stove wicks for each dosage can be determined only by trial. Therefore, it is recommended that when making a 6-hour fumigation the total amount of naphthalene crystals for each stove be divided into six equal parts and that one part be added each hour. When the calculated hourly dose is weighed, its volume can be marked in a small pan or cup which can then be used as a measure for all subsequent doses. By adjusting the stove wicks to vaporize the hourly dosage during the first hour, the rate of vaporization should be uniform during the remainder of the fumigation. After several fumigations many operators learn by observation the correct rate of vaporization and can safely apply the total pan dosage at the beginning, but even then it is strongly advised that frequent examinations be made in order to readjust any wicks which may have varied from the proper position.

In the average greenhouse, circulation during fumigation is obtained only by the movement of warm and cold air and by the buoyancy of the fumes. Observations have indicated that diffusion is greater in large compartments than in small ones. In greenhouses containing 50,000 or more cubic feet, satisfactory results are obtained by using one stove in each 7,000 cubic feet or fraction thereof. In smaller compartments it is advisable to place a stove in each 5,000 cubic feet.

The vapors from fuming naphthalene tend to diffuse with a mushroom effect and frequently they follow the pitch of the roof upward before rolling downward to envelop the plants. It is, therefore, advisable to place stoves at about the same height as the top of the growing plants in order to avoid an excessive concentration of vapor near the stoves, and also to place them in two rows, each row being about one-third of the distance from the sides toward the center.

Light

Exposure to naphthalene vapor during sunlight and photosynthetic action is much less injurious to plants than a similar exposure to such fumigants as hydrocyanic acid gas and volatile nicotine. The most tolerant species of plants growing under normal conditions have consistently shown no detrimental effects from naphthalene fumigation in sunlight, and many of the less tolerant species have been safely fumigated in bright light when other conditions were favorable. When unfavorable conditions exist, however, fumigation in sunlight may aggravate any injury which results from the treatment. In the spring when greenhouse plants are soft, following forced growth in continued cloudy weather, they are less resistant than at other times and should not be fumigated in bright sun.

It is often advisable to take advantage of sun heat for maintaining the necessary temperature, and in cool weather day-time fumigations of carnations and other tolerant plants are satisfactory. In hot weather when excessive temperatures result from closing the ventilators during the day, fumigations should be started in late afternoon and continued into the night until the necessary period of exposure is completed. The less resistant species of plants should be fumigated on cloudy days or at night. When a fumigation is started on a cloudy day and the sun shines before the exposure is completed, it is advisable to discontinue the treatment of susceptible plants; but the fumigation of tolerant plants may continue in the sun until the temperature rises to 95° F.

Temperature

Recrystallization of naphthalene fumes which occurs at 72° F. or lower may be injurious to plants, and temperatures of 95° F. or higher if maintained for several hours are unfavorable to plant growth. Therefore, the temperature limits for fumigation with naphthalene are established at 72° to 95° F.

Theoretically, the capacity of air to hold naphthalene vapor increases as the temperature increases (13), and the greater amount of naphthalene in the air at a higher temperature should kill insects and spiders more easily and quickly. This theory is substantiated by Table 6, which shows that 26.48 and 45.30 percent more common red spiders were killed by fumigations at 90° than at 70° F., and that the treatment was noticeably more effective at 80° than at 70°.

TABLE 6. — RELATION OF TEMPERATURE TO THE EFFECTIVENESS OF NAPHTHALENE FUMIGATION ON THE COMMON RED SPIDER.

Dosage 1 or 1½ ounces per 1,000 cubic feet.
Relative Humidity 75 percent. Exposure 6 hours.
Waltham, Massachusetts. 1934-35.

Temperature	DOSAGE 1 OUNCE		DOSAGE 1½ OUNCES	
	Number of Spiders	Mortality Percent	Number of Spiders	Mortality Percent
70° F.	278	52.51	291	61.85
80° F.	286	83.91	278	88.84
90° F.	137	97.81	120	88.33

Many other experimental fumigations have indicated that variations in temperature between 75° and 85° F. have no significant influence on the effectiveness of the fumigation, and that the permissible range of temperature during fumigation is limited from a practical standpoint by the effect on the plants rather than by the effect on the toxicity of the fumigant.

One or more accurate thermometers placed at strategic locations in the greenhouse should be read frequently.

Air pockets in corners and around certain benches are frequently cooler than the average air temperature, and the temperature in such places should be watched carefully. When the temperature rises above 95° F. and can be lowered only by ventilation, the fumigation should be discontinued.

During commercial fumigations a comparatively constant temperature between 75° and 85° F. is favorable to effective results, and provides a satisfactory leeway for correcting unexpected temperature changes.

Relative Humidity

Relative humidity or the amount of moisture in the air is usually comparatively high in the greenhouse and can be quite easily regulated by careful watering of the soil. When pipe heat is used, however, it is difficult to maintain a constant high humidity, and under such conditions it is frequently necessary to wet the walks and pipes every two or three hours.

Hygrometers or psychrometers for determining the relative humidity should be placed at representative positions in the greenhouse and consulted frequently. A satisfactory type of hygrometer consists of a dry thermometer, a wet thermometer, and a tube of water for supplying the bulb of the wet thermometer with moisture. When both the dry and the wet thermometer read the same, the relative humidity is 100 percent. By interpreting the readings of the two thermometers on a simple chart which accompanies such equipment, the relative humidity is easily determined.

The effect of humidity on the red spider is well shown in Table 7. In this experiment where no fumigant was used, two and three exposures of 6 hours each showed that the mortality of the spiders increased with each increase in the relative humidity, and that this mortality was from 24 to 36 percent greater at 90 percent relative humidity than at 60 percent.

TABLE 7. — MORTALITY OF RED SPIDER AT DIFFERENT HUMIDITY, WITHOUT FUMIGANT.

Temperature 80° F. Exposures 6 hours each.
Waltham, Massachusetts. April 1932.

Relative Humidity Percent	MORTALITY OF RED SPIDER, Percent	
	2 exposures	3 exposures
90	54.28	59.13
80	36.36	49.74
70	29.36	44.44
60	18.65	35.05

In experimental fumigations of active red spiders in which the relative humidity was controlled at 60, 70, 80, and 90 percent, the mortality of the spiders again increased as the relative humidity was increased. As shown in Table 8, this was especially significant when the dosage of naphthalene was 1 ounce or 1½ ounces per 1,000 cubic feet; but when the dosage was increased and the mortality became correspondingly higher, the influence of the humidity decreased and was negligible.

TABLE 8. — RELATION OF RELATIVE HUMIDITY TO EFFECTIVENESS OF NAPHTHALENE FUMIGATION AGAINST RED SPIDERS.

Dosage, 1 or 1½ ounces per 1,000 cubic feet.
Temperature 80° F. One exposure.
Waltham, Massachusetts. April 1931.

Relative Humidity, Percent	MORTALITY OF RED SPIDER, Percent	
	Dosage 1 ounce	Dosage 1½ ounces
90	75.58	99.45
80	70.17	99.20
70	69.81	64.91
60	56.37	42.85

A similar effect on red spider eggs was noted in other experimental fumigations with 1½ ounces of naphthalene per 1,000 cubic feet at 80° F. These fumigations, which killed all of the active red spiders, also killed the eggs at 90 percent relative humidity but permitted 53 and 57 spiders (percentage not determined) to hatch from the eggs fumigated at 75 and 65 percent relative humidity. Further evidence that red spider eggs are more resistant to naphthalene fumigation as the humidity is decreased is indicated by the general abundance of red spider larvae after fumigation at the lower relative humidities, summarized in Table 9. In these experiments the exact number of eggs and larvae present before fumigation is not known, but the evident greater number which survived the treatments at 60 and 70 percent relative humidity is significant.

TABLE 9. — RELATIVE ABUNDANCE OF RED SPIDER LARVAE ON PLANTS FUMIGATED WITH VARIOUS DOSAGES OF NAPHTHALENE AT DIFFERENT RELATIVE HUMIDITY.

Examined 3 days after fumigation. Temperature 80° F.
Waltham, Massachusetts. 1931-32.

Relative Humidity Percent	Dosage per 1,000 cu. ft. Ounces	NUMBER OF RED SPIDER LARVAE ALIVE AFTER —		
		1 exposure	2 exposures	3 exposures
90	1	***	*	*
	1½	*	0	0
	2	0	0	0
80	3	*	0	0
	1	**	***	0
	1½	*	0	0
70	2	*	0	0
	3	*	0	0
	1	****	*	0
60	1½	***	*	0
	2	**	0	0
	3	**	0	0
60	1	***	****	**
	1½	****	**	0
	2	*	**	0
60	3	****	***	****

* — 1 to 10 red spider larvae alive
** — 11 to 25 red spider larvae alive

KEY:

*** — 26 to 50 red spider larvae alive
**** — More than 50 red spider larvae alive

These experiments and several years' experience have proved definitely that a relative humidity of 75 to 80 percent is desirable for the most satisfactory results, and every effort should be made to maintain approximately that condition during fumigation with naphthalene.

Unfavorable Conditions

Few, if any, commercial greenhouses are so nearly air tight and provide so ideal conditions for fumigating as the experimental fumigation chamber in which most of the experiments reported herein were conducted. Leakage, adsorption, air pockets, and failure to maintain satisfactory and constant temperatures and relative humidities all tend to decrease the effectiveness of the treatments. In the experiments reported in Table 10 all of these factors contributed to the results, especially since the fumigations were made in the daytime when favorable conditions are usually more difficult to maintain. The percentage of dead spiders after one and two fumigations is lower than should be expected, but this experiment provides a good example of the occasional need for four successive fumigations to obtain effective control of the red spider.

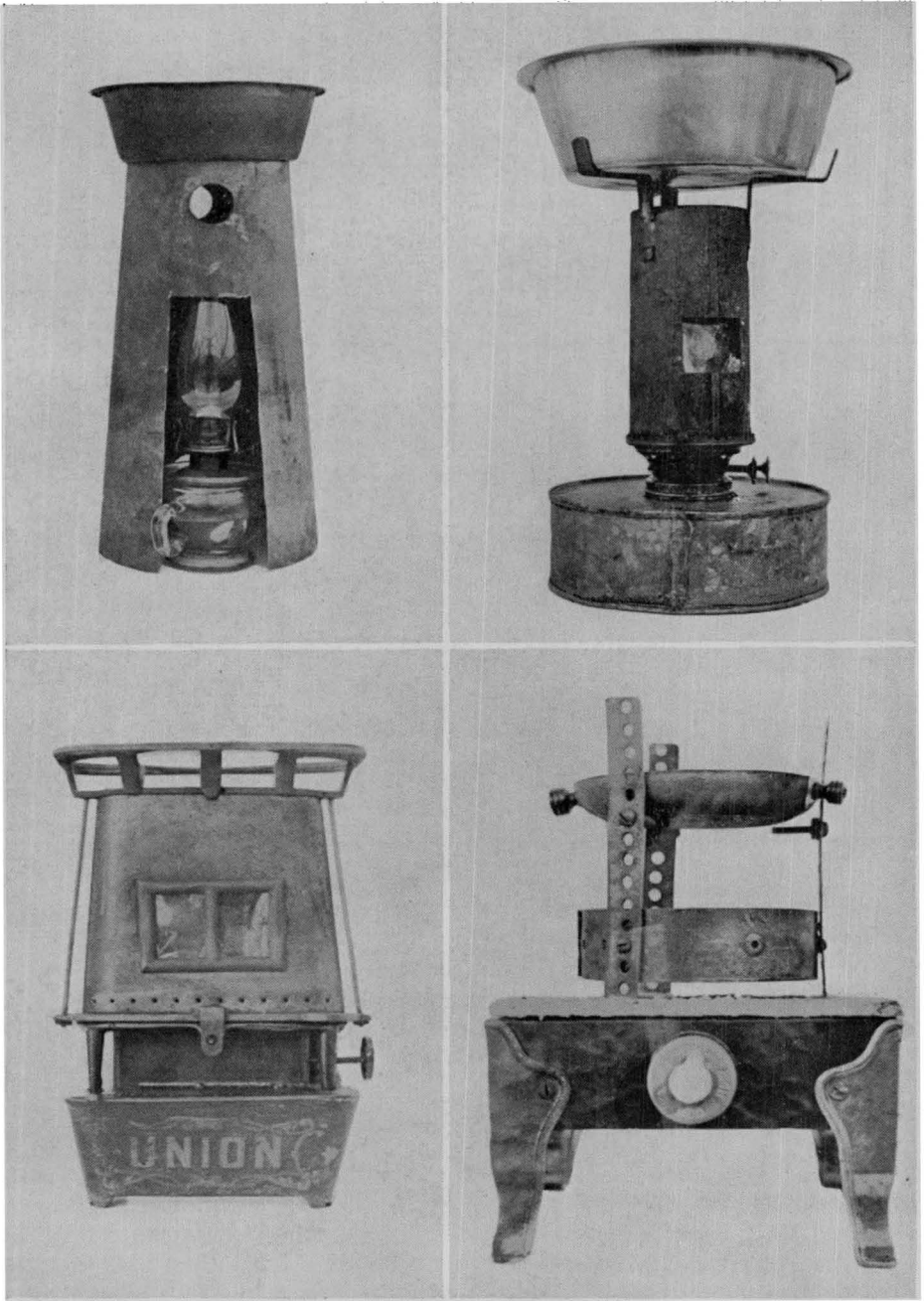


Plate 1. Types of Stoves Used for Naphthalene Fumigation.

Upper Left: Ordinary kerosene lamp with sheet iron cone and pan.

Upper Right: Two-wick stove and chimney designed and sold for Naphthalene fumigation.

Lower Left: Union oil stove manufactured for household use but suitable for naphthalene fumigation.

Lower Right: Electric hot plate and frame to hold sheet iron pan used in experimental fumigation chamber.

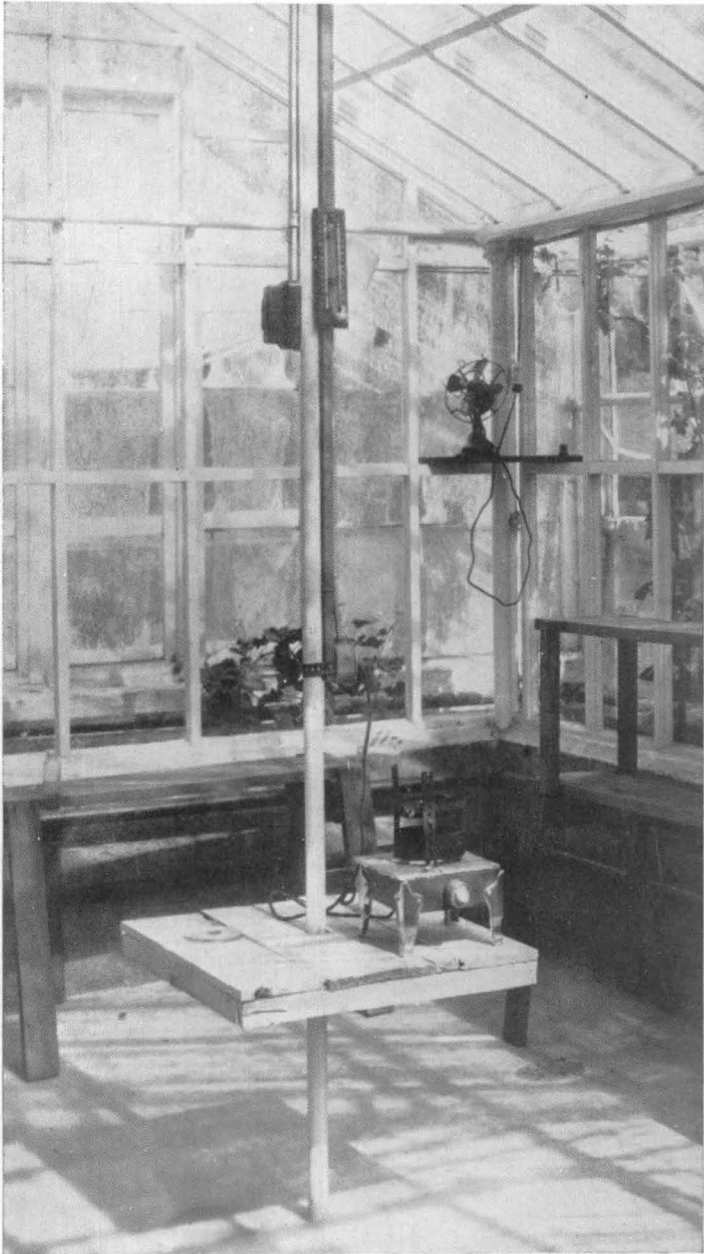


Plate 2. Interior of Experimental Fumigation Chamber, Waltham Field Station. Showing electric hot plate vaporizing unit, fan for circulation, and air pressure thermostat.



Plate 3. Effect of Red Spider Injury to Carnation.

Left: Plant fumigated with naphthalene and free from injury; growth normal.
Right: Plant not fumigated; heavily infested with red spider; growth stunted.



Plate 4. Arrangement of Vaporizing Stoves for Naphthalene Fumigation in a Commercial Greenhouse.

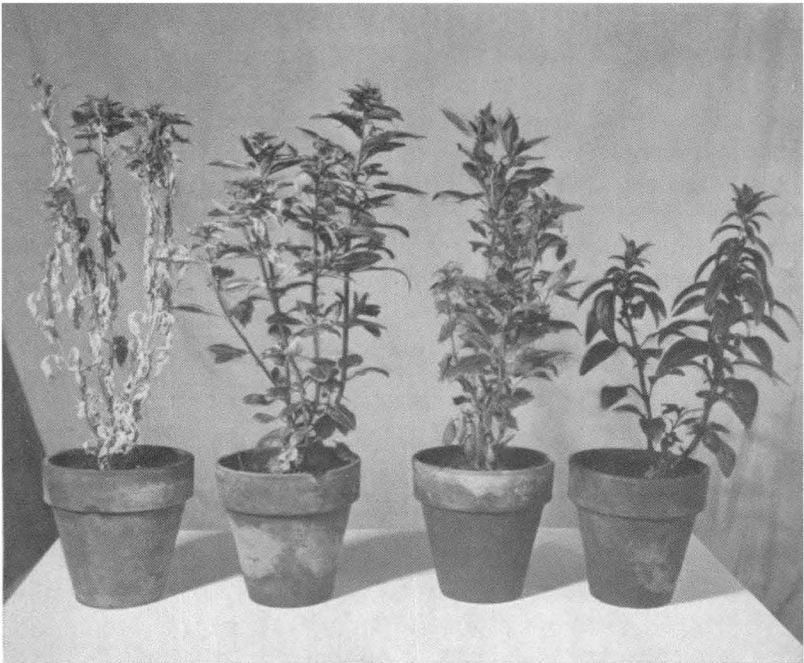


Plate 5. Type of Injury Resulting from Improper Naphthalene Fumigation. Snapdragon Plants.
Left: Severely injured. Center: Slightly injured. Right: Uninjured.

TABLE 10. — EFFECTIVENESS OF NAPHTHALENE FUMIGATIONS UNDER UNFAVORABLE CONDITIONS IN COMMERCIAL GREENHOUSES.

Dosage 2 ounces per 1,000 cubic feet. Crop, Carnation.
 Temperature 75°–90° F. Relative Humidity 60–80 percent.
 Waltham, Massachusetts. October and November 1931.

Number of Fumigations	FIRST SERIES		SECOND SERIES	
	Number of Spiders	Mortality Percent	Number of Spiders	Mortality Percent
1	387	13.69	253	9.09
2	253	35.57	525	57.52
3	285	65.61	396	59.59
4	227	97.78	357	94.30
None (check) .	632	9.18	172	0

COMBINATIONS OF NAPHTHALENE AND OTHER MATERIALS

Speyer in England (16, 17) experimented with naphthalene combined with other chemicals without securing results which were definitely superior to those obtained from naphthalene alone.

Naphthalene and Paradichlorobenzene

Early in the present studies it was apparent that some method for reducing the recrystallizing temperature of the fumes was desirable. Paradichlorobenzene has a lower recrystallizing temperature than naphthalene but is usually injurious to plants in effective doses. A mixture containing 15 percent paradichlorobenzene was apparently safe and could be used satisfactorily at 68° F. or above, while naphthalene alone should be used only at 72° F. or above. Such a mixture was manufactured commercially and used extensively. Experimental fumigations, however, have failed to show that this mixture is significantly superior to naphthalene alone, especially after the two or three successive fumigations which were necessary to secure a reasonable mortality of red spider. Table 11 shows the results of comparative fumigations in adjoining compartments of a commercial greenhouse.

Other Combinations

In 1933 naphthalene in a solid solution with sulfur was reported by Wilcoxon, Hartzell, and Youden (21) to be very effective in a special naphthalene saturator with less injury to sensitive plants.

The same investigators used naphthalene dissolved in motor oil very effectively and safely with exposures of 16 hours in apparatus especially designed for this purpose, and found that the concentration of naphthalene in the air was governed by the amount of naphthalene dissolved in the oil, thus permitting more control over the dosage during fumigation.

Recently, two commercial fumigants similar to naphthalene have been developed and used in Massachusetts. These fumigants are liquids containing benzene ring chemicals closely related to naphthalene in combination with other materials. They are vaporized over stoves and lamps and, in general, require

the same conditions as those recommended for naphthalene fumigation. Experiments indicate that, although the vapor from these fumigants does not recrystallize and become injurious at the lower greenhouse temperatures, comparatively high temperature and humidity are advisable for maximum efficiency. Under favorable conditions they appear to be slightly more effective against red spider than naphthalene and will give satisfactory control of this pest with one or two fumigations.

TABLE 11.—COMPARATIVE EFFECTIVENESS OF FUMIGATION WITH NAPHTHALENE AND WITH NAPHTHALENE-PARADICHLOROBENZENE 85-15 FOR CONTROLLING COMMON RED SPIDER.

Temperature 78° — 85° F. Relative Humidity 80-90 percent.
Waltham, Massachusetts. March 1930.

Fumigant	Dosage per 1,000 cu. ft. Ounces	MORTALITY OF RED SPIDER, PERCENT			
		1 Exposure	2 Exposures	3 Exposures	4 Exposures
Naphthalene	2	12.26	58.58	87.87	98.27
Naphthalene 85 } Paradichlorobenzene 15 }	2	16.07	53.90	90.68	94.48
Naphthalene	3	27.32	97.26	99.61	99.53
Naphthalene 85 } Paradichlorobenzene 15 }	3	41.66	98.33	100.00	100.00
None (check)		4.50			

Compatibility of Naphthalene Fumes with Fungicides and Other Insecticides

Like other fumigants, naphthalene fumes, as used in greenhouse fumigation, leave no residue on the plants which might be injurious to plants when followed by applications of fungicides or other insecticides.

In experimental fumigations by the writer, no injury to carnations resulted when 40 percent free nicotine liquid was combined with naphthalene in the vaporizing pan, and Wilcoxon et al. (21) report safe and effective fumigations with a combination of naphthalene and sulfur.

Carnations bearing the residue from previous applications of Bordeaux mixture have been fumigated with naphthalene regularly in this section without noticeable injury from the treatment.

CONTROL OF OTHER PESTS

As previously stated, naphthalene fumigations are especially effective for combating the red spider. Thrips are also quickly and easily killed by this treatment, but heavy infestations of several other greenhouse pests may be only partially controlled or can be more effectively combated by other means. When regular fumigations with naphthalene are made to control the common red spider, however, other greenhouse pests will be held in check and the crop maintained in a general insect-free condition.

The greenhouse thrips¹ and the onion thrips² are very effectively controlled, and usually with less exposure than is necessary to kill the red spider. Complete control is not always obtained, however, because many thrips hide in the unopened buds where they are partially protected from the fumes. The gladiolus thrips³ is controlled by naphthalene fumigation; but the gladiolus, especially when forced in the greenhouse, may be slightly injured, and the treatment is therefore not recommended.

The green chrysanthemum aphid,⁴ the black chrysanthemum aphid,⁵ the green peach aphid,⁶ and the bean aphid,⁷ the last two being frequently found on carnation, have been completely controlled by two or more fumigations, and it is probable that the treatment is equally effective against all species of aphids likely to be present in the greenhouse. However, one fumigation with naphthalene is not so effective against aphids as one fumigation with nicotine or hydrocyanic acid gas, and the value of naphthalene for this purpose is principally to control aphids when it is being used to combat other pests.

Adult white flies⁸ are killed to about the same extent that aphids are killed; but as is the case when nicotine fumes or hydrocyanic acid gas are used to combat this pest, the majority of the larvae and pupae survive, and repeated treatments or spraying in addition to fumigating may be necessary to give practical control.

The citrus mealy bug⁹ is killed in large numbers by successive fumigations with naphthalene and frequently the soil under heavily infested plants will be covered with their bodies after treatment. However, ten fumigations have not entirely freed the plants of these pests, and the treatment cannot be recommended as a practical control measure.

All stages of the cyclamen mite¹⁰ are resistant to naphthalene fumigation. Furthermore, it is the habit of these pests to live within the unopened buds of flowers and leaves, even working deeply into the crown where they are protected from sprays and fumigants. Frequent fumigations at intervals of 5 to 7 days reduce injury by this pest but will not give complete control. The broad mite,¹¹ a closely related species which is frequently found on the same plants, lives on the exposed surfaces of the leaf and is more effectively controlled by naphthalene fumigation. Smith (18) found that the eggs of this mite are very resistant to this treatment, but by repeating fumigations at least three times at intervals of 5 to 7 days to kill the active stages, this mite was quite satisfactorily controlled.

Bulb mites¹² when exposed to two strong fumigations became sluggish but revived in 24 hours, and mites which were in the soil or in cavities in decayed bulbs were unaffected. In no case did the fumigant penetrate the soil sufficiently to control soil-inhabiting animals. Sowbugs, centipedes, and millipedes are frequently killed when exposed to naphthalene, but large numbers of them are usually sufficiently protected in their hiding places to survive fumigations.

The moths of the greenhouse leaf tyer,¹³ the rose leaf roller,¹⁴ and cutworm species,¹⁵ have been killed by naphthalene fumigation, but the larvae of these

¹*Thrips tabaci* L.

²*Heliothrips haemorrhoidalis* Bouche

³*Taeniothrips gladioli* M. S.

⁴*Coloradoa rufomaculata* Wilson

⁵*Macrosiphon'ella sanborni* Gillette

⁶*Myzus persicae* Sulz.

⁷*Aphis rumicis* L.

⁸*Trialeurodes vaporariorum* Westwood

⁹*Pseudococcus citri* Risso

¹⁰*Tarsonemus pallidus* Banks

¹¹*Tarsonemus latus* Banks

¹²*Rhyzoglyphus hyacinthi* Boisd.

¹³*Phlyctaenia rubigalis* Guen.

¹⁴*Cacoecia rosaceana* Harris

¹⁵Family Noctuidae

insects are seldom killed and the treatment does not constitute a satisfactory control measure.

INJURY TO PLANTS BY NAPHTHALENE FUMIGATION

Unfortunately, naphthalene fumigation is not entirely safe to use on all species of plants or under all conditions, and injury may result if certain precautions are not observed.

Causes of Injury

The usual factors which induce plant injury are (1) fumigation of intolerant species, (2) failure to provide favorable atmospheric conditions (temperature, relative humidity, and light), and (3) improper adjustment of the vaporizing apparatus. These factors actually influence the effect of the fumigation by causing either too great a concentration of the fumes or too long exposure to them.

An excessive concentration of the fumes is most injurious when the melted naphthalene is permitted to boil, causing an unequal distribution and producing temporary supersaturation. There is also evidence that the fumes from boiled naphthalene are broken down by the excessive heat into gases which are more harmful to plants than are the fumes from crystal or melted naphthalene. Poor circulation in the greenhouse resulting in air pockets is often responsible for injurious concentrations of naphthalene in corners. This condition may also be caused indirectly by the recrystallization of naphthalene fumes due to low temperature. The deposit of recrystallized crystals does not injure the foliage immediately, but as each crystal again volatilizes, a strong concentration of naphthalene fumes is created at the place of contact and the plant tissue is burned at that spot.

Injury from too long an exposure to naphthalene fumes may result when the greenhouse remains closed over night after the stoves have been shut off. Possible injury from this cause should be avoided by changing the air as soon as possible after the fumigation is completed, especially when treatments are made on two or three successive days.

Appearance of Injury

Plants which have been exposed to the fumes from boiled naphthalene, or to too great a concentration of fumes from vaporized naphthalene, show wilted and darkened areas on the foliage and stems soon after the injury has occurred. In a few hours the injured areas, which may be the size of a pinhead or may include all the leaves and tender stems of the plant, turn to the characteristic white color of dead but not diseased plant tissue. Usually, the new leaves and tender buds are injured first; and when severe or moderate injury has occurred, new growth generally breaks out below the injured part of the stem, especially on plants which produce buds at the leaf axils.

Injury from too long an exposure to naphthalene fumes is less well defined but usually appears as a premature yellowing and falling of the older leaves. This has been especially noticeable on woody plants such as rose, gardenia, citrus, and oleander, as well as on coleus and some of the larger chrysanthemums. Yellow leaves similar to those following fumigation are also caused by too

forceful syringing or by improper growing conditions, and it frequently appears that the naphthalene only hastens and aggravates the injury, which is primarily due to the poor health of the plant.

Occasionally colored blooms and buds, especially carnations and roses, have been bleached by a prolonged exposure to naphthalene, injury of this kind being more frequent when the growth is abnormally soft and tender.

TOLERANCE OF PLANTS TO NAPHTHALENE FUMIGATION

The tolerance of plants to naphthalene fumes differs greatly. Hartzell (6 and 7) has classified a large number of species and varieties according to their susceptibility in his experiments, and most of the species which are grown in New England greenhouses have been fumigated experimentally by the writer. As a result, certain species of plants are known to tolerate the treatment and others very definitely will not, thus dividing them into three general groups as follows:

(1) Those which are very resistant and are not noticeably injured by slightly excessive concentrations or long exposures. Fumigation recommended as a regular treatment.

(2) Those which have consistently been injured and apparently will not tolerate the treatment. Fumigation not recommended unless plants are to be destroyed.

(3) Those which fall between Group 1 and 2, being tolerant to naphthalene during favorable conditions especially in experimental fumigations but exhibiting a tendency to be injured when slightly unfavorable conditions exist. Fumigation is recommended for this group only when insect injury is severe and when satisfactory control of atmospheric conditions can be maintained. Improved apparatus for fumigating will greatly reduce the danger of injury to plants in this group.

A list of some of the more important plants which fall in Groups 1 and 2 is given in Table 12. All other species are arbitrarily placed in Group 3 since they have been neither outstandingly tolerant nor susceptible in experimental and commercial fumigations.

TABLE 12. — TOLERANCE OF SOME COMMON GREENHOUSE PLANTS TO NAPHTHALENE FUMIGATION.

GROUP 1. Tolerant Plants	GROUP 2. Susceptible Plants
Aspidistra	Asparagus Ferns
Begonia (Chatelaine)	Easter Lily
Boston Fern (Nephrolepsis)	Freesia
Cactus (Opuntia)	Fuchsia
Calendula	Geranium
Carnation	Gladiolus
Centaurea	Iris
Coleus	Kalanchoe
Cyclamen	Narcissus
Dahlia	Nicotiana
English Ivy	Oxalis
Sansevieria	Physalis
	Poppy
	Radish
	Rose (Rambler and Buttonhole)
	Tomato
	Tulip

TABLE 13. — STATUS OF NAPHTHALENE FUMIGATION ON MOST IMPORTANT GREENHOUSE CROPS.

Crop	Naphthalene Fumigation Recommended	Most Important Pests	Controlled by Naphthalene Fumigation	Tolerance to Treatment	Type of Injury if any	Remarks
Begonia (Chatelaine)	Yes	Cyclamen Mite Broad Mite	Slightly Yes	High	Foliage burn	Several successive fumigations necessary.
Calendula	Yes	Red Spider	Yes	High	Foliage burn	Seldom needs treatment.
Carnation	Yes	Red Spider Thrips	Yes Yes	Very high	Slight bleach	Most effective treatment. No injury with favorable conditions. See p. 24.
Chrysanthemum	Conditionally	Thrips Chrysanthemum Midge	Yes No	Low	Blind or deformed buds and yellow leaf.	Not all varieties injured. See p. 25.
Cyclamen	Yes	Cyclamen Mite Broad Mite	Slightly Yes	High	Crippled buds.	Several successive fumigations necessary.
Gardenia	Yes	Mealybug Red Spider	Partially Yes	Medium	Yellow leaf and leaf drop.	Heavily infested plants most likely to be injured.
Lilies	No	Thrips	Yes	Low	Foliage burn	Easter lilies, gladiolus, freesias, tulips, narcissi, likely to be injured. Callas are more tolerant.
Rose	Conditionally	Red Spider Thrips	Yes Yes	Medium	Foliage burn and leaf drop.	Most favorable conditions necessary to avoid injury. See p. 25.

Snapdragon	Conditionally	Cyclamen Mite Broad Mite	Slightly Yes	Medium	Foliage burn.	Most favorable conditions necessary to avoid injury.
Sweet Pea	No	Red Spider	Yes	Low	Foliage burn and bud drop.	Occasionally fumigated, but tolerance is not consistent.
Cucumber	No	Red Spider Thrips	Yes Yes	Medium	Tendril and leaf burn.	Tendrils injured first; fruit retains odor and taste. See p. 25.
Tomato	No	Red Spider	Yes	Low	Foliage tip burn.	Fruit retains odor and taste. See p. 26.

When only one species of plant is grown in a section of greenhouse naphthalene fumigation can be adapted to the requirements of that crop, and frequently a treatment can be regulated to effectively fumigate two or more species growing in the same greenhouse. When susceptible plants are grown in the same section with those which can be fumigated safely, those likely to be injured should be removed during fumigation or the pests should be combated with sprays or dusts. It is not advisable to fumigate a section of mixed plants without regard for the degree of tolerance of the different species.

A summary of the recommendations for fumigating the principal greenhouse crops with naphthalene is given in Table 13.

The desirability of fumigating carnations, roses, chrysanthemums, cucumbers, and tomatoes is considered more frequently than the treatment of other crops and, therefore, the effect of naphthalene on these plants is described separately.

Carnations

Naphthalene fumigation is especially recommended for carnations, and fumigation with it or similar commercial preparations is now a universal treatment for this crop throughout New England. This plant is extremely tolerant to naphthalene and it has been used as the host plant in most of the experimental work with the common red spider. More than forty varieties and color strains have been fumigated with equal safety. During the winter, when there is an excess of cloudy weather, pink blooms have occasionally been faded or bleached slightly following fumigation, but since this effect has not been consistent, the naphthalene appears to be a contributing factor rather than the direct cause. Even should bleaching occur, the resulting loss or decreased value of one or two cuttings is far less than the damage done by an unchecked infestation of the common red spider. The most economical practice is to fumigate thoroughly in the fall so that the plants enter the winter blooming season free from insects and spiders which will not develop seriously at the winter growing temperatures of carnations.

When compared with water syringing as a means of red spider control, regular fumigations with naphthalene produced from 14 to 21 percent more marketable flowers from both good and poor crops of carnations, as shown in Table 14.

TABLE 14. — YIELD OF MARKETABLE FLOWERS FROM CARNATIONS RECEIVING NAPHTHALENE FUMIGATION AND WATER SYRINGE.

Season	Cutting Period	Total Flowers	AVERAGE FLOWERS PER PLANT		F
			Naphthalene Fumigation	Water Syringe	
1929-30	Oct. 1 — May 20†	6,165	13.07	9.76	
1930-31	Sept. 8 — May 13	2,748	6.17	4.00	

*Records furnished by E. F. Guba from data secured in connection with studies of blight (*Alternaria dianthi* S. & H.).

†Average date. Actual date on different benches varied from May 4 to June 3.

Many growers have questioned the effect of subjecting carnations to high temperatures and high relative humidity for 6 hours, but many experimental and commercial fumigations have fully demonstrated the ability of healthy plants to stand these conditions without apparent injurious results.

Roses

Common greenhouse roses of the hybrid tea type, such as Briarcliff, Talisman, and Templar, should be fumigated only when the most favorable conditions can be maintained. They cannot be treated with the heavy dosages or under the partially unfavorable conditions which are tolerated by carnations. Excessive concentrations of naphthalene vapor due to rapid volatilization or poor distribution will burn the new growth and must be avoided. Bleaching of pink varieties is less likely to occur on roses than on carnations. Leaves which have been loosened by forceful syringing invariably turn yellow after fumigation.

Rambler and polyantha type roses, which are frequently forced in pots in the greenhouse, are usually injured by normal fumigations and should never be treated.

Chrysanthemums

Following naphthalene fumigation, the buds of certain varieties of chrysanthemums are deformed or fail to develop. This blindness, which is similar to that caused by improper application of fertilizer, appears to be characteristic of this crop. The plants are especially susceptible during the period of bud formation. Repeated fumigations of buds which have developed from about half grown to full bloom have failed to cause this injury. Varieties appear to have different degrees of susceptibility, and in experimental fumigations the standards, Major Bonnafon, Halliday, and Friendly Rival, and the pompon Golden Nymph, were the most consistently affected, while injury to other varieties has been reported by growers. Blindness did not occur when special apparatus (p. 5) was used, but unless equipment of this nature is available naphthalene fumigation is not recommended for chrysanthemums, especially during the period of bud development and when the above-mentioned varieties are grown.

Cucumbers

Although naphthalene fumigation in the greenhouse was first used to combat the common red spider on cucumbers, this treatment is not now recommended for general use on this crop. The principal reason for discontinuing the practice was the fact that the fruit absorbed and retained the odor and taste of the naphthalene for several days. Much of this taste disappeared after a few hours in fresh air but invariably a sufficient trace of it remained to make the fruit objectionable to people with a sensitive taste. On this crop the tendrils are usually first to show injury, often being shrivelled when no other evidence is present, and this may be followed by burn on the margin of the leaves. Excessive concentrations may also injure the pistillate flowers and prevent development of the fruit. Fumigations of cucumbers soon after they are set in the beds and before they begin to bear will free the plants of pests without contaminating the fruit; and strong fumigations just before the vines are pulled out or when the house is empty is recommended as a means of eliminating thrips and the common red spider between crops.

Tomatoes

Tomatoes are more sensitive to naphthalene fumigation than cucumbers and should be given this treatment only when pest infestation is extremely severe. As with cucumbers, the disagreeable odor and flavor of the chemical is absorbed and retained by the fruit, especially after it begins to color. Injury first appears as a marginal foliage burn on tender new growth.

COST OF NAPHTHALENE FUMIGATION

Naphthalene fumigation is not an expensive operation. After the equipment for fumigating a greenhouse unit is available, the cost compares favorably with that of other effective fumigation treatments.

Permanent equipment consists of vaporizing units and a gas mask of some kind, but with ordinary care this equipment should last for 10 years or more, thus distributing the initial cost over a long period.

Practical vaporizing stoves can be purchased for \$2.00 or \$2.25 each, or satisfactory units can be assembled at home at a cost of 50 cents or more each, depending upon the ability and ingenuity of the individual. The only wearable parts in the stoves are the wicks, which should last for two or three years. Gas masks should be considered a convenience rather than a necessity since many operators do not use them. Furthermore, they have other uses and are valuable safety equipment for many emergencies.

Commercial flake naphthalene costs 8 to 12 cents per pound retail, and 2 to 3 ounces for each 1,000 cubic feet are used in a fumigation.

It is probable that some additional fuel will be necessary to maintain the required temperature but this will be variable and is difficult to estimate. Based on approximate figures in the experimental greenhouses, it would require in the coldest weather approximately 37 gallons of fuel oil at 6 cents per gallon, or $\frac{1}{4}$ ton bituminous coal at \$7.00 per ton, to raise the temperature 15° to 25° F. above normal temperatures for a 6-hour fumigation period; while in cool weather about 12½ gallons of fuel oil at 6 cents per gallon, or 1/10 ton of bituminous coal at \$7.00 per ton, would be sufficient.

Most fumigations are managed by the grower or his most reliable regular help so that no additional labor is necessary, but if additional labor is necessary an expense of 6 hours labor at 30 cents an hour should be charged to the fumigation.

An estimate of the cost for fumigating with naphthalene in a greenhouse 200 feet long, 30 feet wide, and 10 feet high (average), containing 60,000 cubic feet is as follows:

	<i>Initial Cost</i>	Maximum	Minimum
Stoves, 1 for each 7,000 cu. ft.:			
9 at \$2.25 (purchased)	\$20.25	
9 at .50 (homemade)		\$4.50
Gas Mask	5.00	None
		<hr/>	<hr/>
Totals	\$25.25	\$4.50

Operating Cost

	Maximum	Minimum
Naphthalene, 3 or 2 ozs. per 1,000 cu. ft.:		
3 ozs. per 1,000 cu. ft. — 180 ozs. or 11¼ lbs. at 10c	\$1.125	
2 ozs. per 1,000 cu. ft. — 120 ozs. or 7½ lbs. at 10c		\$0.75
Fuel for stoves:		
2 gals. kerosene at 17c	.34	.34
Additional fuel for heat:		
Cold weather — 37 gals. oil at 6c	2.22	
Cool weather — 12½ gals. oil at 6c		.75
Additional labor:		
6 hours at 30c	1.80	None
Total	\$5.485	\$1.84

PROCEDURE FOR FUMIGATING WITH NAPHTHALENE

Choose the time for fumigating according to the weather. When it is cool start the fumigation about 9 a. m. on cloudy days; when it is warm, start about 4 p. m. Do not fumigate on windy days.

Remove susceptible varieties of plants from the greenhouse whenever practicable.

Water all potted plants, wet the walks, and be sure that soil in the benches is moist, thus raising the relative humidity to about 80 percent as determined from a hygrometer or a psychrometer.

Close ventilators and stop drafts through broken or loose glass.

Raise temperature to 75° to 80° F., as determined from an accurate thermometer, and adjust heating equipment to maintain that temperature.

Determine the cubical contents of the house by multiplying the length by the width by the average height. Supply a stove for each 7,000 cubic feet in a large house, or for each 5,000 cubic feet in a small house, placing them just above the top of the plants.

Determine the amount of naphthalene crystals necessary for treatment at the rate of 2 or 3 ounces per 1,000 cubic feet, depending upon the tightness of the house. Determine the proportionate amount for each stove and divide this by 6 to give the amount for each stove for each hour. Mark this hourly dosage in a glass or cup which can be conveniently used as a measure.

EXAMPLE: A house 200 feet long, 40 feet wide, 10 feet average height, contains 80,000 cubic feet. At the rate of 1 stove for each 7,000 cubic feet, use 12 stoves placed about 15 feet apart. At the rate of 3 ounces of naphthalene per 1,000 cubic feet, 20 ounces per stove ($80 \times 3 = 240 \div 12$) is necessary and should be divided at the rate of 3½ ounces ($20 \div 6$) per stove per hour for 6 hours.

Light stoves and adjust wicks to a low flame, being sure that they do not blaze up in one corner.

Put one hourly dosage of naphthalene in each pan.

After one hour add another hourly quota to each pan, and if necessary adjust the flame of the lamp by raising the wick if some naphthalene remains or by lowering it if the material has vaporized before the required time. Repeat this operation each hour until six hourly doses have been vaporized.

If the melted naphthalene should boil or should vaporize in less than half

the required time, it is usually advisable to stop the fumigation and change the air in the greenhouse; but if the naphthalene has vaporized too rapidly in only one or two lamps the danger of plant injury is not great and the fumigation can usually be continued after adjusting the lamps.

If the temperature unavoidably rises above 95° F. or drops below 70° F. during the exposure, the fumigation should be discontinued and the house ventilated.

When pipe heat is used to maintain the necessary temperature, the relative humidity may decrease rapidly making it advisable to wet the walks after the third hour.

After the fumigation is completed, the air in the greenhouse should be changed by opening the doors and ventilators. In cool weather this should be done gradually to avoid a rapid drop in the air temperature.

SUMMARY

Commerical flake naphthalene, costing 8 to 12 cents a pound, when vaporized in the greenhouse controls the common red spider and the greenhouse thrips very effectively and is a satisfactory method for combating these and other pests.

Naphthalene fumes kill by penetrating the respiratory system of insects and spiders causing paralysis and death.

Eggs of the red spider were killed by two or more successive fumigations using 3 ounces of naphthalene per 1,000 cubic feet for 6 hours, and old eggs were killed more quickly than newly laid eggs. The larva, protonymph, and adult female of the red spider appear to be more easily killed than other stages. Two successive fumigations at a dosage of 2 ounces or more of naphthalene per 1,000 cubic feet have resulted in practically perfect control of red spider under favorable experimental conditions. Dosages of more than 3 ounces of naphthalene per 1,000 cubic feet have frequently caused supersaturation and plant injury, and dosages of less than 2 ounces per 1,000 cubic feet have usually required more than two successive treatments to be effective.

In controlled experiments the vaporization and confinement of three-fourths ounce of naphthalene per 1,000 cubic feet produce a noticeable effect on the red spider, and an exposure to this concentration for three hours has killed 85 percent or more of these pests. Under average greenhouse conditions some of the fumes escape or are absorbed by the soil and benches so that the most satisfactory dosage is 2 to 3 ounces per 1,000 cubic feet, and a total exposure of 6 hours is recommended for effective results.

In commercial greenhouses where it is difficult to maintain favorable atmospheric conditions, three or four successive fumigations are frequently necessary to give effective control. The treatment is satisfactory whether the interval between fumigations is one, two, or three days, and the time to fumigate should be determined by suitable weather conditions.

Although various types of stoves, lamps, and special saturators are available for vaporizing naphthalene for fumigating, a two-wick coal-oil stove is the most practical under average greenhouse conditions. In these stoves the crystals are melted to increase vaporization but the melted naphthalene should never boil. A uniform vaporization can be obtained by dividing the total dosage for

each stove into six equal parts and adding one part each hour, adjusting the wick so that each hourly quota is vaporized in one hour. In large greenhouses one stove unit should be used in each 7,000 cubic feet of space, but in small compartments a stove unit for each 5,000 cubic feet is advisable.

Resistant species of plants can be safely fumigated in the sunlight. In cool weather sun heat can be used to aid in maintaining the necessary temperature. In warm weather high temperature can be avoided by starting the fumigation in the late afternoon and continuing into the evening. The less resistant species of plants should be fumigated only on cloudy days or at night.

Although the effectiveness of naphthalene fumigation increases as the temperature increases, the recrystallization of the fumes at about 72° F., and the undesirable effect on the plants at 95° F. or higher, limit the temperature range between these points. In commercial fumigations a nearly constant temperature between 75° and 85° F. is practical and effective.

High relative humidities are unfavorable to red spider development and in a series of experiments in which no fumigant was used 59 percent of the red spiders were dead after three 6-hour exposures at 90 percent relative humidity compared to a 35 percent mortality after a similar exposure at 60 percent relative humidity.

In experimental fumigations the treatment was significantly more effective at 80 and 90 percent relative humidity than at 60 and 70 percent relative humidity, especially when 1 ounce and 1½ ounces of naphthalene per 1,000 cubic feet were used. The greater effectiveness of naphthalene fumigation at the higher humidities was also evident from the consistently greater number of red spider larvae which hatched from eggs fumigated at the lower humidities. Relative humidities of 75 to 80 percent are most satisfactory during naphthalene fumigation.

Because of the promising results from the first experiments with naphthalene, several combinations of materials have been used to enlarge the scope of the treatment and to simplify the operation. Locally a mixture of 85 parts of naphthalene and 15 parts of paradichlorobenzene was effective but not significantly superior under experimental conditions. Mixtures of naphthalene and nicotine were compatible and the residues from sulfur and Bordeaux mixture were not harmful on fumigated plants. Other investigators used solutions of naphthalene in sulfur and in motor oil very effectively in special apparatus. Two commercial liquid fumigants containing chemicals similar to naphthalene and used in the same way appear to give very satisfactory control of the red spider, and can be used safely at temperatures lower than are safe with naphthalene alone.

Greenhouse thrips and onion thrips are readily killed by naphthalene fumigation. The most common species of aphids and the adults of the greenhouse white fly are also killed but not as effectively as with nicotine fumes or hydrocyanic acid gas. Mealybugs are only partially controlled. Cyclamen mite is quite resistant to naphthalene fumigation, but the broad mite, a closely related species, is well controlled. Bulb mites and soil inhabiting pests are killed when exposed but because of their habits are seldom controlled. Leaf roller and leaf tyer moths are killed by strong fumigations but the larvae are more resistant.

Naphthalene fumigation may cause injury to plants if certain precautions are not observed, the usual causes being (1) fumigation of intolerant species, (2) failure to provide and maintain favorable atmospheric conditions, and (3) improper adjustment of the vaporizing apparatus. Melted naphthalene should never be allowed to boil nor to closely approach boiling in the vaporizing stove since the fumes given off under these conditions are injurious to plants. The recrystallization of naphthalene vapor from supersaturation or exposure to temperature below 72° F. may also injure plants. After the exposure of the fumigation is completed, the air should be gradually changed without lowering the temperature too rapidly.

Plant injury following improper naphthalene fumigation usually appears as white areas of dead but not diseased plant tissue, as yellow leaves which soon drop, and as bleached or faded areas on the petals of colored flowers.

Among the most common greenhouse crops, begonia (Chatelaine type), Boston fern, carnation, and cyclamen are very tolerant; while geranium, lilies, rambler rose, and tomato are usually injured. Most other species and varieties are near the border line between safety and injury and should be fumigated only when pest injury is severe and favorable conditions can be maintained. Greenhouses containing both tolerant and susceptible species of plants should not be fumigated unless the susceptible species are removed.

Fumigation with naphthalene or similar commercial preparations is a universal treatment for carnations in New England. In experimental plantings naphthalene fumigated carnations produced 14 to 21 percent more marketable flowers per plant than those receiving regular syringing with water.

Hybrid tea type of roses can be safely fumigated under the most favorable conditions, but the rambler and polyantha type are invariably injured.

Certain varieties of chrysanthemums are blinded by naphthalene fumigation during the bud forming period but are tolerant to this treatment at other times.

Cucumber and tomato fruits absorb and retain the odor and taste of naphthalene for several days after fumigation, making them objectionable to people with a sensitive taste. The tendrils and pistillate flowers of cucumbers may also be injured, and marginal burn on the leaves of both cucumbers and tomatoes occasionally results.

The initial cost for equipment to fumigate a 60,000 cubic foot greenhouse may vary from \$25.25 if the fumigating stoves are purchased to \$4.50 if they are homemade. The operating cost including fuel for raising the temperature in cold weather may vary from \$5.49 to \$1.84 for each treatment depending on the conditions.

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