Sulfur Dioxide Fumigation of Table Grapes

UNIVERSITY OF CALIFORNIA
DIVISION OF AGRICULTURE AND NATURAL RESOURCES

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Sulfur Dioxide Fumigation of Table Grapes

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This publication is dedicated to
Dr. Klayton E. Nelson, Department of Viticulture and Enology, UC Davis,
and Dr. John M. Harvey, USDA-ARS Horticultural Crops Laboratory,
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Their research and the research of others who pioneered the use of
sulfur dioxide on table grapes has passed the test of time.

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Introduction

Although table grapes are perishable, they can be stored more than 2 months before sale and shipped worldwide. Several factors allow grapes this long postharvest life: a low respiration rate, low-temperature storage, and sulfur dioxide (SO_2) fumigation. These factors work together to allow extended storage and long-distance shipping. Even at storage temperatures near 32°F (0°C), table grapes that have not been fumigated fall victim to fungal infection and decay within several weeks.

The most important pathogen of stored table grapes is "gray mold," commonly referred to as "Botrytis," which is caused by *Botrytis cinerea* Pers. Botrytis is especially troublesome in cold storage because of its tolerance for low temperatures and its vigorous growth rate. Before harvest, many pathogens (including Botrytis) infect berries and cause bunch rots. Preharvest rainfall on grapes greatly increases the incidence of gray mold: the spores infect berries within 15 to 20 hours under cool (55°–75°F [13°–24° C]), moist conditions.

As early as 1915, California grape growers and shippers knew that the fumes produced by burning sulfur would reduce decay in grapes shipped by rail. In 1925, Winkler and Jacob published recommendations for applying sulfur dioxide from pressurized cylinders rather than burning sulfur. Their new technique produced predictable, regular results. By the 1930s, many growers and packers were fumigating their grapes with sulfur dioxide before cooling them. Later, periodic (usually weekly) fumigations during cold storage became standard practice.

VARIABILITY OF SULFUR DIOXIDE PENETRATION INTO BOXES

Conditions are extremely variable among grape storage facilities, among rooms in a given facility, and even within an individual storage room, with respect to the efficiency with which administered sulfur dioxide penetrates into boxes of grapes. This variability is associated with the following factors:

1. The design and types of boxes and within-box packs, including barriers to gas penetration such as box design, liners, vents, wraps, cushion pads, etc.

2. The flow of air carrying sulfur dioxide during fumigation, and whether it is forced through pallets or circulated adjacent to pallets.

3. The air speed adjacent to pallets during circulating-air fumigation. Air speed is influenced by the speed, design, and number of fans, by pallet stacking patterns, and by the length and width of the between-pallet channels through which the air must flow.

4. The position of pallets in the fumigated rooms, with respect to distance from the sulfur dioxide inlet.

5. The position of boxes within pallets, ranging from most exposed (on the outside of the pallet) to least exposed (on the inside of the pallet).

6. The materials used to construct the storage room, especially sulfur dioxide absorptive versus non-absorptive wall coverings.

7. The humidity within the fumigated rooms, and the free moisture present in or on box, wall, and floor surfaces exposed to the fumigant.

Because there are so many causes of variation, no simple system of sulfur dioxide fumigation can be uniformly recommended. Instead, the manager of each facility must have sulfur dioxide fumigation calibrated and monitored in individual rooms based upon actual CT levels. Rooms should be evaluated when full and when half-full, and other variables that might be encountered during a grape storage season should be included.

At high rates, sulfur dioxide fumigation causes grape injury evidenced by bleaching of the berry skin. Bleaching is especially obvious in dark-colored varieties, but it is noticeable even in light-colored fruit. Bleaching occurs first at the capstem end of the berry or around cuts, bruises, punctures, and other injuries that weaken or penetrate the berry skin.

For the more than 70 years that sulfur dioxide has been used for fumigation, grape growers have decided how much fumigant to apply by balancing two opposing needs: the need to maximize decay control and the need to minimize fruit bleaching. The amount of sulfur dioxide needed to control Botrytis spread in storage is close to the concentration that causes some bleaching to the fruit. Even today, some cold storage operators believe that a total absence of bleaching indicates that the dosage of sulfur dioxide is insufficient. However, we now know that undamaged fruit can be stored for long periods under a controlled fumigation program without decay or bleaching.

Until 1986, sulfur dioxide and other sulfites were classified by the U.S. Food and Drug Administration (FDA) as GRAS (Generally Regarded As Safe), and as such required no registration. In postharvest use on grapes, sulfur dioxide is now classified as a pesticide, and is under the regulatory control of the U.S. Environmental Protection Agency (EPA). Through the efforts of the registrant and distributor (Snowden Enterprises Inc. of Fresno, California), working in conjunction with the California Table Grape Commission, the FDA, and the EPA, a tolerance of 10 parts per million (ppm) was set for sulfur dioxide residues in table grapes. The registrant then initiated procedures with the EPA to obtain approval of a label that would allow sulfur dioxide use for control of posthar-

vest decay, and ensure residue levels under 10 ppm.

Some storages find that the strict requirement that sulfur dioxide residues be kept below 10 ppm is difficult to meet while using traditional fumigation practices. Also, continuing changes in regulations that govern worker safety and environmental pollution place additional limitations on sulfur dioxide fumigation practices. To address these issues, the industry organized a research task force of scientists from the University of California at Davis and Berkeley, California State University Fresno, the USDA Agricultural Research Service in Fresno, and private industry, and instructed the group to modernize the procedures for using sulfur dioxide. This bulletin is the result of the research conducted by members of the task force between 1987 and 1991. Traditional practices have been evaluated and modified to maintain effective postharvest decay control and minimize sulfur dioxide damage to the fruit. Compliance with future regulatory requirements is the individual operator's responsibility.

The Normal Harvest and Storage Sequence*

Field packing includes the picking, trimming, packaging, and palletizing of grapes in the field. As clusters of grapes are picked in the field, pickers inspect them visually for small, off-color, damaged, or decayed berries. The pickers remove these inferior berries. Especially important are decayed berries that could infect other berries either by contact or mycelial growth during storage. Most table grapes are field packed, and several types of packs are available. The plain or naked pack predominates during most of the season. Fruit bunches can also be packed in polyethylene bags or wrapped in tissue paper (the advantages and disadvantages of each type of pack will be discussed further on in this manual). Packed boxes are placed on pallets, and are then handled as palletized units. Trucks transport palletized boxes to the storage or shipping facility.

A small proportion of table grapes are picked into large field boxes and brought to a central location where they are packed. After packing, handling practices are the same for these fruit as for field-packed fruit.

At the cold-storage facility, the pallets usually are straightened, and then strapped, banded, or wrapped in netting to stabilize the pallet. Grapes are then fumigated quickly with sulfur dioxide and precooled to slow the spread of existing decay or germination of Botrytis spores that would create new sources of decay. After precooling, grapes are either transported directly to market in refrigerated trucks or placed in long-term storage.

If grapes are stored before shipping, they are held in refrigerated storage rooms. Pallets are usually stacked two or three high in lanes designed to maximize the use of space, yet allow sufficient air movement between pallet lanes so that cooling can continue, cold temperatures can be maintained, and the room can be effectively fumigated. Repeated fumigation of a room with sulfur dioxide is normally conducted on a 7-day schedule.

Postharvest Diseases of Table Grapes

All of the postharvest diseases of table grapes are caused by fungi. Commonly observed diseases include gray mold (Botrytis), caused by *Botrytis cinerea;* black spot, most frequently caused by *Cladosporium herbarum;* nested rot, caused by *Rhizopus* spp.; smut, caused by *Aspergillus niger;* and blue mold, caused by *Penicillium* spp.

Botrytis (gray mold)

Botrytis diseases are among the most common and widely distributed diseases of fruits, vegetables, and greenhouse crops worldwide. Gray mold is the most destructive of the postharvest diseases of table grapes, primarily because of its ability to develop at temperatures as low as 31°F (−0.5°C), the weakness of grapes' ability to resist infection by this fungus, and the abundant white surface mycelial growth it produces from infected berries, which causes spread to adjacent healthy berries. In darkness and under humid conditions, the abundant hyphal filaments develop and spread rapidly from berry to berry so that an uncontrolled infection from a single berry can infect an entire package of grapes. Small pockets of decay resulting from berry-to-berry mycelial spread are known as "nesting." Botrytis rot can be diagnosed easily by the characteristic "slipskin" condition that develops. Brown areas of fruit skin infected with Botrytis will slip freely when rubbed with the fingers, leaving the firm underlying pulp exposed.

Temperatures should be maintained as close as possible to 31°F (−0.5°C), since temperatures 4° and 8°F (1.7° and 3.9°C) higher can result in a 2- or 3-fold increase in decay development (fig. 1).

Other characteristics contribute to the prevalence of this fungus. In the field, it readily develops tar-colored, long-lived resistant bodies called "sclerotia" on infected plant parts, and these can survive unfavorably dry or host-free periods. The sclerotia germinate in moisture to produce abundant masses of gray-colored spores that infect

* For a more detailed discussion, see K. Nelson, *Harvesting and Handling California Table Grapes for Market,* Bulletin 1913 from ANR Publications, University of California, 6701 San Pablo Ave., Oakland, California, 94608-1239.

newly emerging shoots, flowers, and berries. As the growing season progresses, additional spores are produced from bunch rot infections and other infected plant parts, increasing the density of airborne spores.

Botrytis spores can infect berries in several ways. Early season infection of the stigmata of opening grape flowers will leave behind fungus-infected fragments of the flower that increase the subsequent inoculum level inside the developing cluster. Some evidence shows that these stigmal infections remain on the berry as it develops, but become inactive (latent), and develop later when the berry matures. Other latent infections may arise when spores germinate and penetrate the berry surface, but then stop developing until the berry matures. Latent infections are especially troublesome because they reside within the grape tissue where they cannot be eradicated by preharvest fungicides or postharvest sulfur dioxide applications. Although spores can penetrate and infect berries without wounds under prolonged (15 hours), cool (55° to 75°F [13° to 24°C]), moist conditions, spores placed in mechanical wounds that penetrate the cuticle and epidermis of the berry do not require moist conditions for infection. These wounds can be caused by physiological cracking, tight clusters, insect or bird damage, or handling at harvest. Botrytis can be very destructive even in seasons when rainfall is sparse. The proportion of postharvest decay originating in early season latent infections and direct infections through wounds is uncertain.

REQUIREMENTS FOR AN EFFECTIVE BOTRYTIS CONTROL PROGRAM

IN THE FIELD:

1. Pack well-trimmed grapes. Do not misalign liners and vents or over-fill packages.

2. Do not pack broken, split, cracked or damaged berries.

3. After a rain that thoroughly wets the clusters, allow a minimum of 3 days before harvest.

INITIAL FUMIGATION:

1. Completely precool and fumigate as rapidly as possible after harvest.

2. Forced-air initial fumigation is more efficient than fumigating with circulating air.

IN THE COLD-STORAGE ROOM:

1. Use total utilization fumigation, so no ventilation is required to remove surplus sulfur dioxide. The longer sulfur dioxide exposure times in total utilization fumigation reduce sulfur dioxide variability between boxes.

2. Calculate the amount of sulfur dioxide needed based on number of boxes and box type and pack.

3. Weekly fumigation is more effective than fumigation at longer intervals.

4. Air speed past pallets during the first one or two hours of fumigation should be greater than 140 feet per minute (fpm). Stack pallets neatly with four inches between lanes, and use slotted air ducts or plenums to improve air distribution.

5. When possible, store boxes with similar penetration characteristics in the same room.

6. As inventory decreases, consolidate fruit in the least number of rooms and minimize open lanes.

7. Following fumigation, use gas monitoring equipment to verify appropriately low concentrations of sulfur dioxide in the room before you allow personnel to re-enter.

Several cultural practices can reduce the incidence of postharvest Botrytis. By removing desiccated, infected grapes from vines during winter pruning, growers can reduce the inoculum produced in the following season. Systemic and contact fungicides reduce flower and bunch rot infections. Opening the leaf canopy by removing the leaves adjacent to clusters improves the coverage of fungicide applications, increases air speed around clusters, and decreases humidity, and all of these factors are associated with a decreased incidence of disease. Rigorous trimming of infected berries from clusters at harvest and before packing is critical to reducing postharvest decay.

Rainfall, especially if mature clusters become thoroughly wet, dramatically increases Botrytis. Harvest should be suspended for at least 3 days after any rain that thoroughly wets the clusters. This allows time for infections to develop enough for visual identification so that infected berries can be removed. Furthermore, to maximize control of these infections in storage after a rain, packers should use a package that does not impede sulfur dioxide penetration, such as plain or naked pack. Even with these precautions, rained-on fruit should be segregated from fruit harvested in rain-free periods, and should be sold as soon as possible.

Minor diseases

"Black spot," caused primarily by *Cladosporium herbarum* but also by *Alternaria* sp. and *Stemphylium* sp., develops slowly under refrigerated storage, and marks berries with characteristic black spots. The darkened, decayed tissue of these black spots is more resistant to slight pressure than are Botrytis infections. Black spot does not spread by nesting (berry-to-berry spread), and black spot infections adjacent to the capstem increase the incidence of shatter. Disease incidence increases after fall rains, and is most common on Emperor variety grapes.

A rapid and very destructive nested decay of grapes is

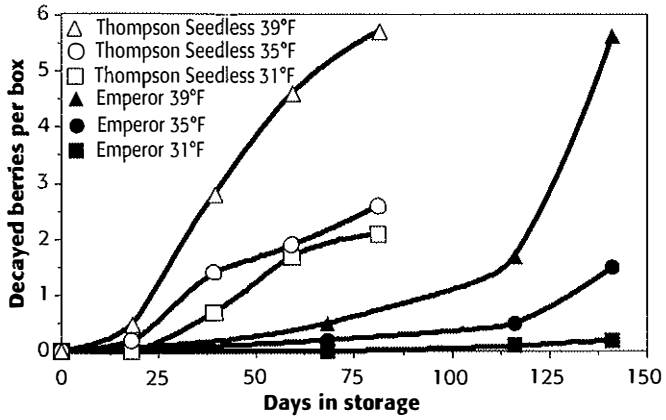


Fig. 1. Decay development in Thompson Seedless and Emperor table grapes after storage at 31°, 35°, and 39°F (from Nelson and Richardson 1967).

caused by *Rhizopus stolonifer* and *Rhizopus arrhizus.* However, since both pathogens require a minimum storage temperature of 68°F (20°C) for development, their occurrence indicates gross temperature mismanagement after harvest.

"Smut," caused by *Aspergillus niger,* gets its name from the abundant black spores it produces. Although capable of causing rapid nested decay, it is like the *Rhizopus* spp. in that it cannot develop under refrigeration. "Blue mold," caused by *Penicillium* spp., develops slowly from infected wounds on or within single berries during refrigerated storage. Blue mold does not cause nested decay.

Other postharvest disorders

Other disorders observed on grapes in storage include berries scarred as a result of powdery mildew, *Uncinula necrix.* This fungus does not continue to develop after harvest, but the preharvest injury it causes can seriously detract from berry quality. Other disorders, such as freezing, internal browning, waterberry, insect feeding injuries, and mechanical damage to berries are often observed after harvest, and the storage manager should be familiar with their appearance.

Decay Control Using Sulfur Dioxide

Botrytis cinerea inoculum can come from several sources such as spores in the air, on boxes, and on the surface of berries; microscopic latent infections in berries; or visibly infected berries that escaped the trimmer's knife. Initial sulfur dioxide fumigation kills all exposed spores as well as many of those inside fresh wounds on the berries. Only those infections that are within berries can survive this process. Periodic fumigation during subsequent storage will kill the aerial mycelial growth produced from these established infections and reduce the resultant berry-to-berry spread of decay.

CT product

Sulfur dioxide exposure has to be sufficient to kill the spores and mycelia of *Botrytis cinerea* in the stored grapes, so the storage manager needs a way to measure the quantity of fumigant in the storage room atmosphere. The action of a toxicant against organisms is often described in terms of (1) the toxicant concentration and (2) the amount of time it remains in contact with the target organism. Typically, the concentration and the time of contact are multiplied together; the product of these is the concentration × time, or "CT," product. For sulfur dioxide fumigation, concentration is measured in parts per million (1 ppm = 1 part by volume in 1 million parts of total volume). Time is measured in hours. When both values are known, a CT product can be calculated:

$$\text{CT} = \text{average } SO_2 \text{ concentration (ppm)} \times \text{fumigation time (hours)}$$

For example, if 100 ppm sulfur dioxide is present for 1 hour, the CT product is 100 ppm-hours (100 ppm × 1 hour). If a 100 ppm concentration is present for a half hour, the CT product is 50 ppm-hours (100 ppm × 0.5 hour). Similarly, if 50 ppm sulfur dioxide is present for 2 hours, the CT product is 100 ppm-hours (50 ppm × 2 hours). By defining the magnitude of sulfur dioxide exposure in a single term, the CT product makes the fumigant's action easy to quantify under the varied conditions that exist in cold-storage facilities.

Studies to determine the minimum sufficient CT values for sulfur dioxide fumigation have shown that a CT of 100 ppm-hours kills both the spores and the mycelia of *Botrytis cinerea*, and controls decay in storage (figs. 2 and 3). These studies employed sulfur dioxide concentrations ranging from 25 to several thousand ppm, temperatures from 32° to 68°F (0° to 20°C), fumigation periods ranging from several minutes to 2 hours, and humidity conditions characteristic of grape storage. This 100 ppm-hour exposure should be considered the minimum acceptable level for initial and storage fumigation. Storage facilities can probably exceed this minimum several times over without developing high sulfur dioxide residues or significant bleaching injury.

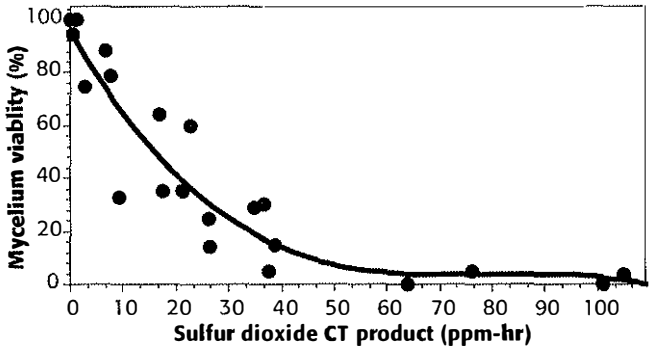


Fig. 2. Influence of SO_2 CT product on the viability of the mycelium on *Botrytis cinerea*-infected Thompson Seedless grapes. Each point represents the percentage of berries with living mycelium out of a total of 30 fumigated grapes. All tests were conducted at 32° to 34°F (0° to 1°C).

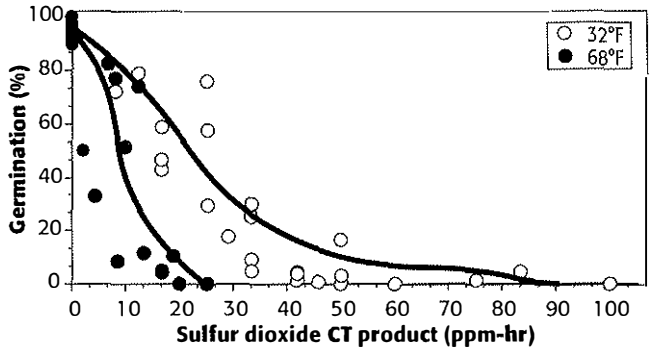


Fig. 3. Influence of SO_2 CT product on the germinability of *Botrtis cinerea* spores at 32°F (0°C) and 68°F (20°C). Each point represents the percent germination of 200 to 400 spores.

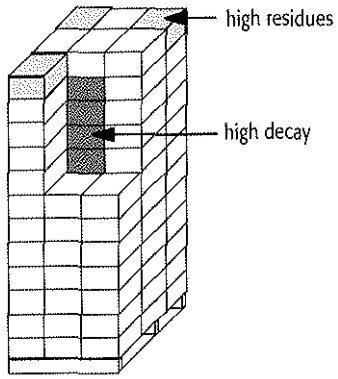


Fig. 4a. Location of boxes that are most likely to have high SO_2 residues and boxes that are most likely to have decay.

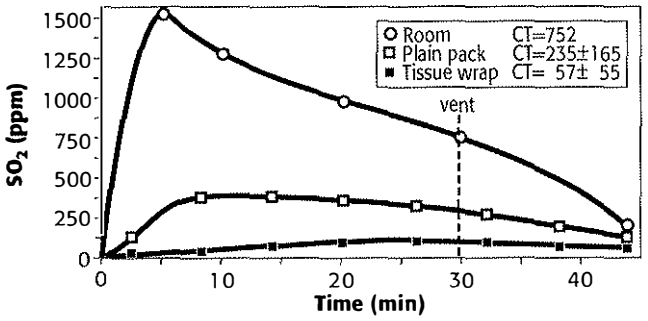


Fig. 4b. Room and in-box CTs of plain-pack and tissue-wrapped Calmeria grapes in EPS boxes.

Measuring Sulfur Dioxide in the Air

Some cases of poor or irregular decay control can occur even with sulfur dioxide fumigation. Postharvest decay is a consequence of insufficient exposure to sulfur dioxide, while injury to grapes, mostly bleaching and high sulfur dioxide residues, results from excessive exposure. Furthermore, excessive gas levels require subsequent gas removal from the storage room atmosphere by scrubbing, add unnecessary expense, and increase the opportunity for accidental exposure of workers to the fumigant. For these reasons, storage room operators should have a means to determine the actual concentration of sulfur dioxide within the storage rooms and within individual grape packages.

Remote sampling is recommended, since entering rooms during fumigation is unsafe. The maximum safe workplace concentration of sulfur dioxide is 2 ppm (8-hour time-weighted average). Even a very brief exposure to 100 ppm is immediately hazardous to life and health. More than 20 ppm sulfur dioxide is beyond the rated capacity of canister gas masks; above this concentration, only self-contained breathing apparatus (SCBA) devices can be used. Special training and certification are required for use of SCBA to enter rooms containing sulfur dioxide. Even with SCBA, regulations require that a similarly equipped partner be available to effect rescue if necessary, and any skin exposed to the gas may be subject to injury. Higher concentrations of sulfur dioxide are best measured by pump-type samplers, and within-box CTs are best measured by dosimeter tubes up to levels as high as 250 ppm-hours. At CT levels higher than that, a pump-type sampler should be used.

Infrared analyzers can be used to measure sulfur dioxide gas concentrations. They can measure low concentrations of sulfur dioxide, but they are expensive. They also require accurate calibration using standard gas, and must be corrected for water vapor before use. Although infrared analyzers are useful research tools, we do not recommend their routine use.

Pump-type gas samplers

The concentration of sulfur dioxide in room air is easily determined using a pump-type gas sampler. This instrument is a sealed metal syringe that takes in 100 ml of gas when a user pulls out the handle. As the gas enters the pump, it passes through a glass tube inserted into the pump inlet. Sulfur dioxide changes the color of a reagent packed in the tube. The length of reagent column that changes color can then be measured against markings on the outside of the tube, and shows the concentration of sulfur dioxide in parts per million or percentage of total

atmosphere. Sulfur dioxide concentrations from 1 ppm to thousands of ppm can be measured using this simple system. A similar principle is employed in the slower bellows-type sampler, only the sampled volume is much greater so the minimum sensitivity is increased to 0.1 ppm.

To sample within rooms or within packages during fumigation, storage technicians must use an air pump in combination with tubing (preferably polypropylene, Teflon, or Tygon) that does not absorb sulfur dioxide. Rotary peristaltic pumps can withdraw samples from multiple locations, but these are expensive. An inexpensive aquarium-type diaphragm air pump works well enough, and battery-powered aquarium pumps are available at some pet stores.

Sulfur dioxide dosimeters

The sulfur dioxide CT product within a package can be measured using gas dosimeters that were developed originally for human safety purposes. The dosimeters are sealed glass tubes containing sulfur dioxide-reactive substrates. One end of the tube is broken off just before use. Sulfur dioxide then diffuses passively along the length of the tube; the extent of diffusion is recorded as a color change in the substrate, and calibrated lines imprinted on the tube quantify the dosage in ppm-hours. This method requires no processing or special equipment beyond reading the dosimeter tubes themselves.

We evaluated two types of dosimeter tubes: Gastec–Sensidyne "Dosimeter Tubes" (Gastec Corporation, Ayase City, Japan), which indicate sulfur dioxide dosages of up to 100 ppm-hours by a green-to-yellow color change; and Dräger "Diffusion Detector Tubes" (Dräger Werk AG, Lübeck, Germany), which indicate sulfur dioxide dosages of up to 150 ppm-hours by a pink-to-yellow color change. Both are available from industrial safety supply companies. The Gastec tubes give a very stable color reaction that does not change after sulfur dioxide exposure, while the Dräger dosimeter tubes are less stable after exposure, and so require immediate reading for best accuracy.

The tubes should be placed inside grape packages just before fumigation and then removed and recorded as soon as it is safe to re-enter the fumigation room. Take care that grapes, tissue wraps, or other packing materials do not block the tube's open end. If water or grape juice enters the tube, inaccurate readings can result.

If decay has been a problem within a room, the best places to monitor fumigant levels are the places most likely to have insufficient exposure. Boxes at the center of a pallet receive less sulfur dioxide than the outside boxes, which have more vents exposed to the room atmosphere. The top corner boxes have more vents exposed than any other package in a pallet, and will typically have higher CT values after fumigation (fig. 4a). Pallets from locations with low air speed and those near the air return generally have lower CT values than pallets in other locations. However, pallets closest to the air supply will tend to have higher values. Packages containing tissue-wrapped or plastic-bagged grapes generally have lower CT values than plain-packed grapes (fig. 4b).

CT values of 100 ppm-hours or more are adequate. If the color change exceeds the scale printed on the tube but has not completely bleached the reagent to the end of the tube, you can assume a CT product of between 100 and 250 ppm-hours. If all of the color has changed throughout the length of the tube, the CT product is in excess of 250 ppm-hours: the box CT could be 300, 600, or 900 ppm-hours. This condition indicates that excessive sulfur dioxide exposure may have occurred during fumigation. When high CT readings indicate potentially excessive sulfur dioxide levels, storage technicians can reduce the dosage in subsequent fumigations until some of the dosimeter tubes are not completely bleached.

MONITORING FUMIGATION EFFECTIVENESS

The quantity of sulfur dioxide that penetrates into grape boxes should be monitored in every room used for initial fumigation or long-term storage. Pay attention to differences in the construction materials, ducting, and coil area used in each room. In addition, each room must be evaluated both when full and when half-full. Use these evaluation guidelines:

1. Measure gas penetration into palletized boxes by placing dosimeter tubes among the grapes in the center-most boxes on the pallets. The dosimeter tubes are calibrated directly in ppm-hours of CT. Boxes should be monitored in at least three lanes of pallets, at both the upwind and downwind ends of lanes, and at high and low pallet elevations.

2. Determine the severity of Botrytis decay and its spread by frequently inspecting grapes taken from pallet locations that receive the highest and lowest sulfur dioxide exposures. Tests indicate that the pallets that receive sulfur dioxide-laden air first and the pallets located just before the air returns to the cooling coils fit these criteria. Center boxes should be monitored for decay.

3. Monitor sulfur dioxide residues in grapes starting as early as possible in the storage period. You can expect to find the highest residue levels in the lowest pallets near the upwind end of the pallet rows, and in outside top corner boxes of the pallets. Because sulfur dioxide residue analyses are highly variable, view any residues above 3 ppm with concern.

Calculation of a room's CT

Room CT levels are typically too high for measurement with a dosimeter tube. The CT of a room can be estimated by using a pump-type sampler to determine the room sulfur dioxide concentration and recording the time that the reading was taken. Sulfur dioxide levels need to be determined 5, 10, 20, 40, and 60 minutes after the start of fumigation. Levels drop slowly after the first hour, so beyond that point hourly or less-frequent readings will suffice. Table 1 shows sample data for calculating a room's CT. The sample room has received a fumigation dose of 227 ppm-hours.

TABLE 1. Example of calculating a room CT

Time		Time	SO_2	ppm-
Minutes	Hours	interval*	*ppm*	hours
5	.083	.083	1,200	99.6
10	.167	.084	550	46.2
20	.333	.166	220	36.5
40	.667	.334	75	25.1
60	1.000	.333	30	10.0
120	2.000	1.000	10	10.0
Total CT				227.4

*The time interval is the number of hours since the previous reading

Air Pollution Considerations

In many parts of California, the release of sulfur dioxide into the outside atmosphere is prohibited. Traditional fumigation methods eventually require either that sulfur dioxide be released or that the storage room air be cleaned by a scrubbing system. All new facilities that use traditional fumigation techniques must use scrubbers to dispose of excess sulfur dioxide after fumigation.

Residues

Normal accumulation of sulfur dioxide residues by repeated fumigation can be related to general damage done to the grapes. Sulfur dioxide residues on the grape skin open microscopic pores in the grape cuticle, creating entry points for sulfur dioxide gas during subsequent fumigations. Other conditions that may accelerate this normal accumulation of residues are warm fruit, low fruit maturity, excessive use of sulfur dioxide gas, and grape variety.

Less-mature Flame Seedless and Thompson Seedless grapes accumulate significantly more residues after fumigation than more mature grapes. These differences may result from differences in the thickness or porosity of the grape skin and wax on the skin.

A single initial fumigation with sulfur dioxide creates little detectable residue in the grapes, normally well below 10 ppm. However, when grapes are held in storage for a long period and are gassed repeatedly at concentrations of 1,250 ppm or more, residue levels may increase. Any residue higher than 10 ppm is not acceptable, and could result in the impoundment and holding of grapes until their residue levels decrease to less than 10 ppm.

There is always the possibility that during routine operations, too much gas might occasionally be admitted to the storage room, or the excess gas in the room might not be vented quickly enough. These problems are often caused by human error.

The grape variety, the sulfur dioxide dose associated with the fumigation error, and the number of times the grapes have been fumigated affect the time required for residues to drop below 10 ppm. Higher-level errors, especially those that occur later in the storage season, increase the time needed for residues to drop below 10 ppm. When several different varieties are stored in the same cold storage room and are fumigated simultaneously, sulfur dioxide residue levels vary according to variety. The different varieties also lose their sulfur dioxide residues at different rates.

Following a fumigation error, sulfur dioxide residues decrease with time for Calmeria, Christmas Rose, Flame Seedless, and Thompson Seedless grapes (figs. 5a and 5b, figs. 6a and 6b). The grape variety, extent of the error (30 minutes or 60 minutes at 10,000 ppm), and total length of time the grapes have been in storage all have some bearing on how long it takes grapes to return to levels below 10 ppm sulfur dioxide. Higher-level errors made after longer periods of storage consistently decrease or even eliminate the grapes' ability to reduce their sulfur dioxide residues to marketable levels.

In general, Thompson Seedless grapes take up the most sulfur dioxide residues, followed by Flame Seedless and Christmas Rose. Calmeria grapes consistently take up the least sulfur dioxide residues (figs. 5 and 6). When Crimson Seedless grapes are fumigated with Flame Seedless and Thompson Seedless, both low and high fumigation error levels left the Crimson Seedless with higher 24-hour sulfur dioxide residues (data not shown).

Also of interest is the location of sulfur dioxide residues on or in the grape berry during early, middle-, and late-season storage. Early in the storage season, most sulfur dioxide residues are found on the skins. Later on, the pulp residue levels increase and are similar to the skin residue levels after 9 weeks' storage (fig. 7). While the data indicate that grape skins are the major sink for sulfur dioxide residues after fumigation, some residues do migrate into the pulp. With increased storage time, the

–*Continued on p. 13*

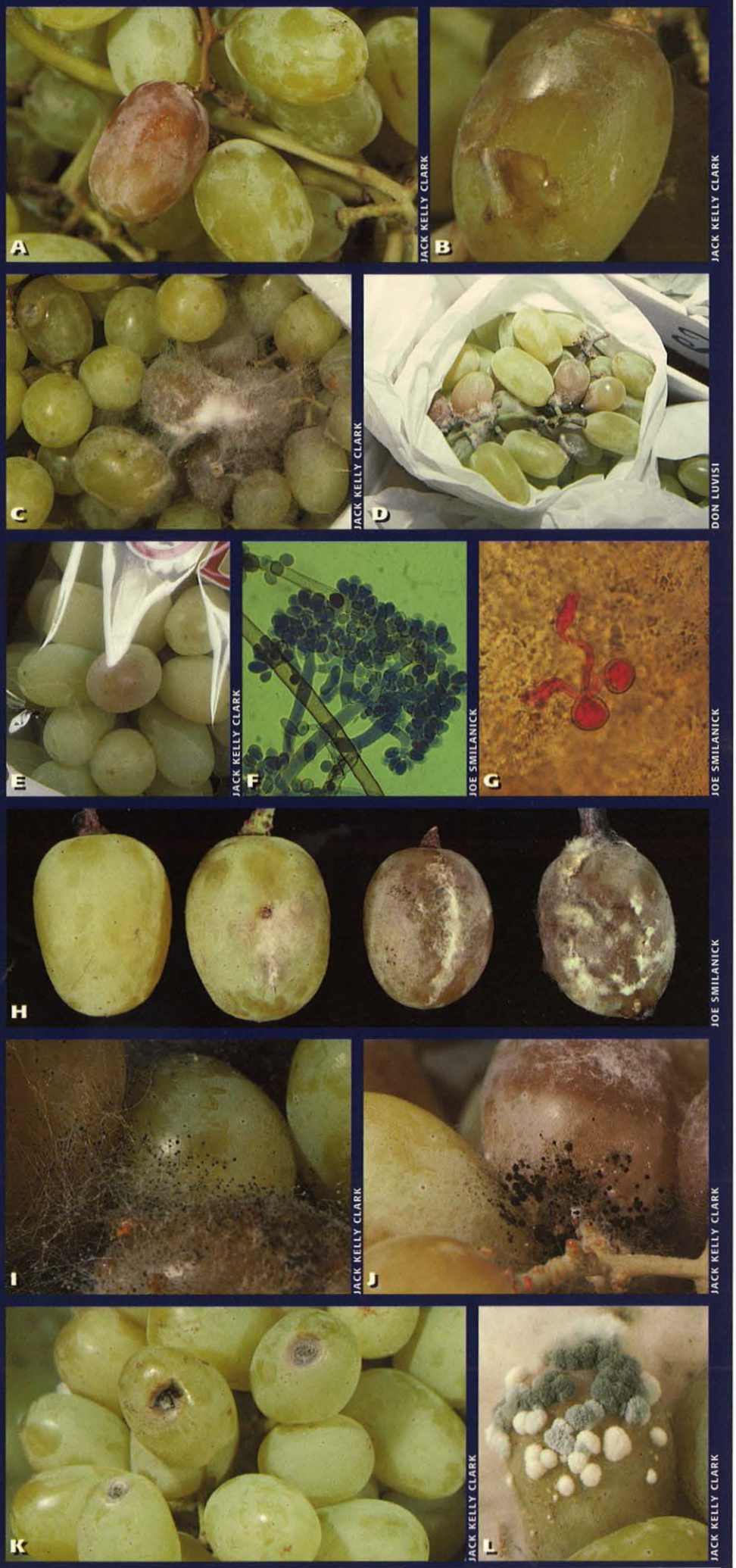


Plate I

Diseases

A. Typical brown coloration of a Botrytis-infected Thompson Seedless berry. This condition is often the result of a preharvest infection that continues to develop under cold conditions.

B. When berries are infected with Botrytis, the skin separates from the berry. This condition, called "slipskin," is a diagnostic characteristic of Botrytis infections.

C. An advanced Botrytis infection from a single berry has produced a surface growth infecting adjacent berries. The mycelial spread to adjacent berries is known as a "nest," or "nesting."

D. Tissue-wrapped Thompson Seedless grapes with Botrytis-infected berries. This fruit missed the initial fumigation. Subsequent storage fumigations prevented mycelial growth, but did not eliminate or prevent the internal growth of latent infections. The "nest" in plate I-C did not receive adequate SO_2 during storage.

E. Thompson Seedless grapes in a polyethylene bag with no SO_2 fumigation. Note the development of a Botrytis infection on a single berry.

F. Cluster of conidia (spores) of *Botrytis cinerea*. Germination requires about 20 hours of moist conditions at 50°–70°F (10°–21°C), or about 7 days at 32°–36°F (0°–2.2°C).

G. Germinating spores can penetrate directly into berries under moist conditions, although wounds or injuries are major points of entry.

H. Progressive development of Botrytis infections on Thompson Seedless grapes 5, 10, 15, or 20 days at 10°C after inoculation with Botrytis spores.

I. *Rhizopus* sp. infection of Thompson Seedless grapes. Although this organism causes rapid nested decay, it does not develop under refrigeration. Its appearance indicates poor temperature management.

J. *Aspergillus niger* is called "smut" because of its black, sooty spores. It requires warm temperatures, and can also cause nested decay.

K. *Cladosporium herbarum* is one of several fungi that cause "black spot" of grapes in storage. The fungus develops under cold conditions and does not cause nested decay. Black spot is more prevalent on grapes harvested after rain.

L. *Penicillium* spp. cause "blue mold" in storage. The pathogen enters the berry through a wound. Blue mold does not cause nested decay, and is rarely a significant problem.

Plate II

Disorders

A. Powdery mildew, caused by *Uncinula nectrix,* on the rachis of Redglobe grapes.

B. This crack on a Redglobe grape berry, caused by an insect feeding injury, has become infected by *Botrytis cinerea* before harvest.

C. Rain-damaged grapes that have been colonized by *Botrytis cinerea.* Gray spores are visible.

D. The rachis on the Redglobe cluster at left shows the collapsed, straw-brown color characteristic of drying, while the cluster at right is unaffected.

E. Although SO_2 treatment cannot stop the rachis from drying, it does help retain a straw color as shown, rather than the dark brown color that would appear without SO_2.

F. Sulfur dioxide has penetrated the wounds on this Redglobe grape and severely bleached the surrounding tissue.

G. Brown, bleached areas on excessively gassed Thompson Seedless grapes. The brown areas, which develop after removal from cold storage, severely reduce the grapes' marketability.

H. Internal browning, shown here in a Thompson Seedless grape, is a physiological problem that develops during cold storage.

I. Berries 1 and 4 show internal browning; berry 2 is a normal, undamaged berry; and berry 3 shows freezing, or low-temperature injury.

J. A crushed berry (*arrow*) in a packed box. Crushed, split, and damaged berries increase SO_2 residues, since the gas seeps into the areas surrounding the wounds and bleaches them.

K. Field decay in Perlette grapes resulting from bird damage. Note the Botrytis-infected berry adjacent to other bird-damaged berries.

L. Field decay in Perlette grapes. When trimming away decayed grapes, all surrounding infected berries should be removed.

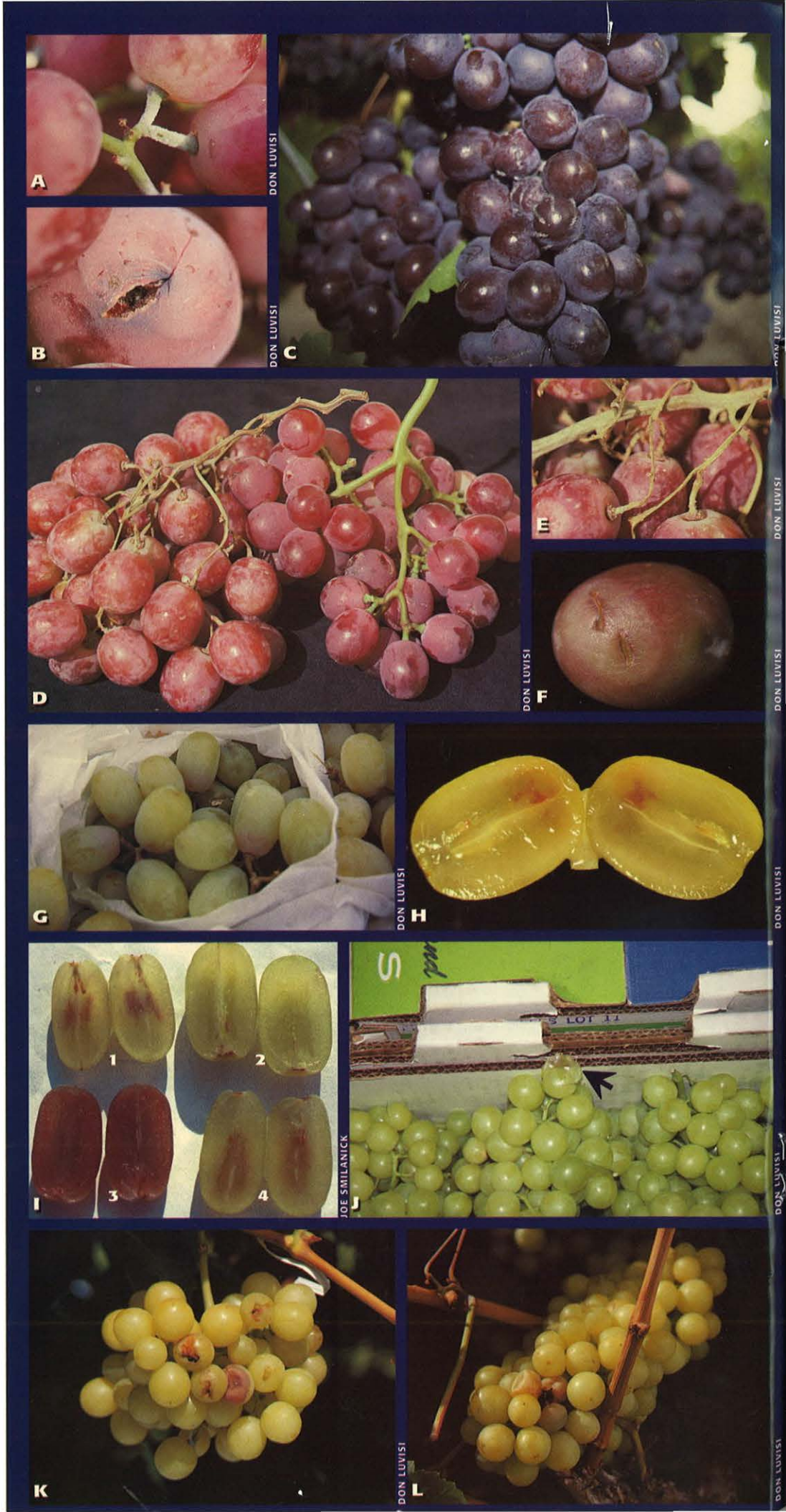
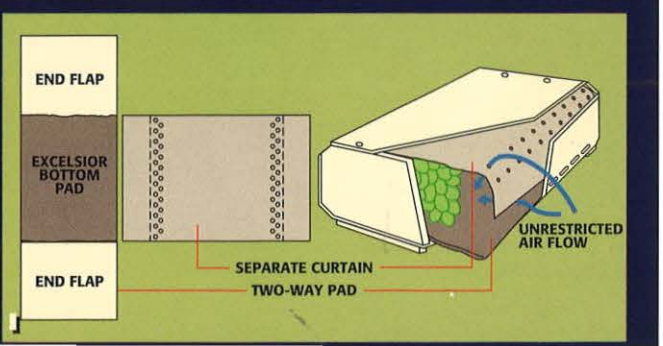


Plate III



Packs and Boxes

A. ***Left:*** **Plain, or naked pack.** ***Right:*** **Lower left corner of box; note the liner with vent holes.**

B. ***Left:*** **Tissue-wrapped Thompson Seedless grapes in an EPS (expanded polystyrene) container.** ***Right:*** **Lower right corner of box, showing moderately loose tissue wrap; note the mesh curtain covering the top of the fruit.**

C. ***Left:*** **Bagged Thompson Seedless grapes in a fiberboard box.** ***Right:*** **Lower left-hand corner of fiberboard container; note the bags and the absence of curtains or mesh covers.**

D. Tissue-wrapped Thompson Seedless grapes. The box on the left has tightly covered metric wrap (no fruit are showing). The box on the right has open-top tissue wrap.

E. Three barriers to sulfur dioxide gas penetration: (1) tissue wrap; (2) bubble top pad; (3) top curtain.

F. Fiberboard container with its corners clipped to improve air circulation. The resulting air passage lines up from box to box along the full length of the pallet.

G. TKV box with crowned center. The box's vent holes are plugged by misalignment of liners and the top curtain.

H. Fiberboard containers with the vents between two boxes lined up. Note that the vent cut-out at one location has not been removed.

I. Diagram of vents and air flow in a TKV box with a two-way pad and separate curtain.

Plate IV

Storage Monitoring

A. Center box from a three-box by three-box layer. Since the center box in a pallet has the poorest SO_2 penetration, it is the best monitoring location for determining the adequacy of an SO_2 fumigation program.

B. Arrows point to the box locations best for sulfur dioxide monitoring in three common pallet stacking configurations: (1) 2 × 3; (2) 2 × 3 × 2; (3) 3 × 3.

C. Inserting a dosimeter tube down into the center of a tissue wrap.

D. Dosimeter tube inserted into tissue wrap. Ensure that the tube opening is not blocked by tissue, and that the tube does not penetrate a berry.

E. A dosimeter tube, showing color change from green to yellow. Arrow points to CT = 40 ppm-hours (CT 40 = 20 ppm for 2 hours).

F. A series of dosimeter tubes showing CT readings between 40 and 100 ppm-hours.

G. Pump and SO_2 detector tubes used to monitor room SO_2 levels and calculate room CTs.

H. Misalignment restricts air flow between pallets. Blocked or poor lanes between pallets can increase the variability in SO_2 doses between boxes and pallets.

I. Air flow is monitored by using light yarn attached to a telescoping aluminum pole. Light yarn can trace air currents too weak for detection with an anemometer.

J. A hot-wire anemometer used to measure air speed.

K. Several types of temperature measuring devices. *Far right:* a type "T" thermocouple; *center:* a thermometer with a hypodermic probe; *top* (above the thermometer): a thin-stem thermometer.

L. Portable scrubber for SO_2. This device uses a spray of alkaline water to remove SO_2 from the cold room after fumigation.

–*Continued from p. 8*

relative amount of sulfur dioxide residue in the pulp of the grape increases. Initially, sulfite residues are converted to sulfates in or on the grape skin. During long-term storage, sulfate migrates into the pulp, and there it is resistant to removal. This also explains why sulfur dioxide residues decrease more slowly after fumigations later in the storage season.

Increases in temperature and air circulation increase the rate of sulfur dioxide residue reduction. When grapes subjected to a fumigation error are stored with increased air circulation at 45°F (7.2°C), the sulfur dioxide residue levels decrease more quickly than with grapes held under normal refrigerated storage conditions. If storage-room temperature is increased but air circulation is not, grapes tend to show increased residues at first, but decreasing levels over time. The packing box apparently acts as a reservoir for sulfur dioxide, and at higher temperatures the box releases this sulfur dioxide. Some of the sulfur dioxide is apparently picked up at first by the grapes, but with time, residues continue their downward trend.

TABLE 2. Effect of berry damage on SO_2 accumulation

Type of damage	SO_2 residues Thompson Seedless	Flame Seedless
	ppm	
Intact berry (no damage)	2.3	2.2
Loose capstem	2.8	3.2
Bruised berry	6.6	3.3
Botrytis-infected berry	10.8	17.9
Split or crushed berry	23.6	18.5

Damaged berries and sulfur dioxide residues

Sulfur dioxide is highly soluble in water, so damaged berries tend to accumulate higher residues than intact berries (table 2). Split or crushed berries and Botrytis-infected berries accumulated the highest residues. The accumulation of unwanted residues stresses the importance of removing all damaged berries during the picking, trimming, and packing operations. Overfilled boxes and compaction during the lidding operation can cause additional split berries after packing has been completed. Even berries with weakened or loosened capstem attachments as a result of rough handling have elevated sulfur dioxide residues. Close examination often reveals that berries thought to have loose capstem attachments actually have torn skins or cuticles.

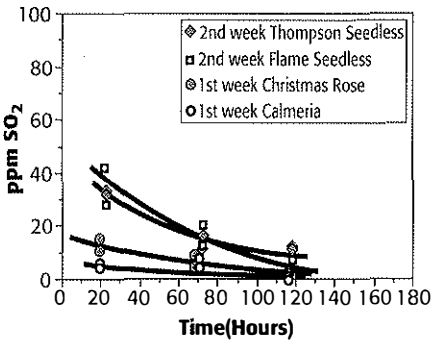


Fig. 5a. Sulfur dioxide residues after a low-error fumigation of berries that occurred after 1 or 2 weeks in storage.

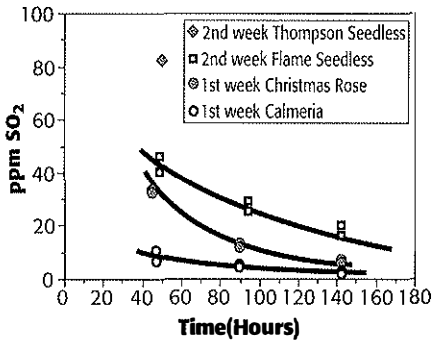


Fig. 5b. Sulfur dioxide residues after a high-error fumigation of berries that occurred after 1 or 2 weeks in storage.

High-error fumigation: 10,000 ppm for 1 hour

Low-error fumigation: 10,000 ppm for 30 minutes

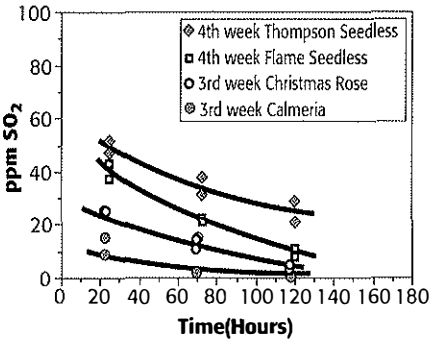


Fig. 6a. Sulfur dioxide residues after a low-error fumigation of berries that occurred after 3 or 4 weeks in storage.

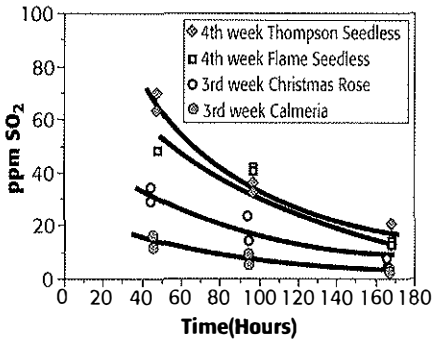


Fig. 6b. Sulfur dioxide residues after a high-error fumigation of berries that occurred after 3 or 4 weeks in storage.

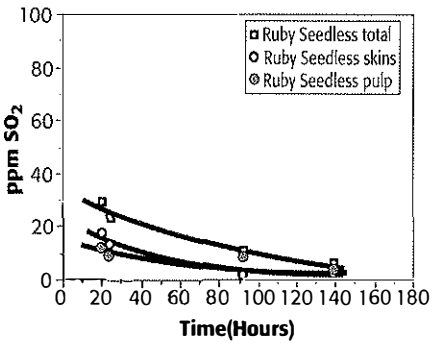


Fig. 7. Sulfite residues in Ruby Seedless grape skin and pulp that occurred after 9 weeks' storage.

Fumigation Practices

The amount of sulfur dioxide that effectively controls Botrytis varies according to the length of time that grapes are exposed to the gas. As previously noted, the dosage of sulfur dioxide that will kill Botrytis spores or mycelia during fumigation is 100 ppm-hours. Why, then, do storage facilities have frequent problems with decay developing in grapes that are regularly fumigated? This dosage should be easy to obtain, considering that a traditional sulfur dioxide program for initial fumigation uses 5,000 to 10,000 ppm and results in room air CTs of more than 2,000 ppm-hours during the 30-minute fumigation cycle. This is 20 to 40 times higher than the recommended 100 ppm-hours. A traditional storage fumigation program commonly uses 2,500 ppm of sulfur dioxide for 30 minutes, obtaining room air CTs in excess of 900 ppm-hours. The answer is not simple. The key is that rather than the amount of gas in the room atmosphere, the critical factor is the amount of gas that penetrates the package and is in contact with the fruit.

There are two methods currently used for fumigation: the traditional method and the newly developed total utilization method. Both methods give adequate decay control, but they differ in the quantity of sulfur dioxide used and the methodology of its application.

Extensive research and testing has demonstrated a relationship between the CT in the total room atmosphere and the CT within a packed box of grapes. The amount of sulfur dioxide penetrating a box of grapes, expressed as a percentage of room CT, has been used to develop the sulfur dioxide factors used in the following tables and graphs.

Although our investigations have concentrated on dry-coil systems, CTs and dosimeter tubes can be used to evaluate in-box sulfur dioxide dosage with both dry-coil and wet-coil refrigeration systems. Wet-coil heat-transfer systems have a built-in scrubbing capability, and do not present problems with residual sulfur dioxide when properly managed.

Traditional Fumigation

This method may be used for initial fumigation when the grapes are first received at a facility, and for weekly fumigation during long-term storage of table grapes. Relatively high sulfur dioxide concentrations are added to the room, and after a fumigation cycle of 20 to 30 minutes the remaining sulfur dioxide is scrubbed or vented from the room atmosphere.

Traditional initial fumigation

Initial fumigation can be accomplished using either of two air flow systems – circulating-air fumigation or forced-air fumigation – and each can be used either in combination with initial cooling or as a separate operation. In circulating-air fumigation, air flows past, but not through, palletized boxes of grapes. The penetration of sulfur dioxide into the innermost boxes on a pallet depends on the speed of air currents past the pallets and the combination of box and packing materials used. The air speed should be at least 140 feet per minute for maximum penetration. Figure 8 shows that lower air speeds can significantly reduce sulfur dioxide penetration. By misaligning liner vents and box vents or packing grapes in plastic bags or paper wraps, packers may reduce sulfur dioxide penetration. In circulating-air initial fumigation, sulfur dioxide penetration often exceeds 50 percent of room air CT, but it can vary widely among pallets.

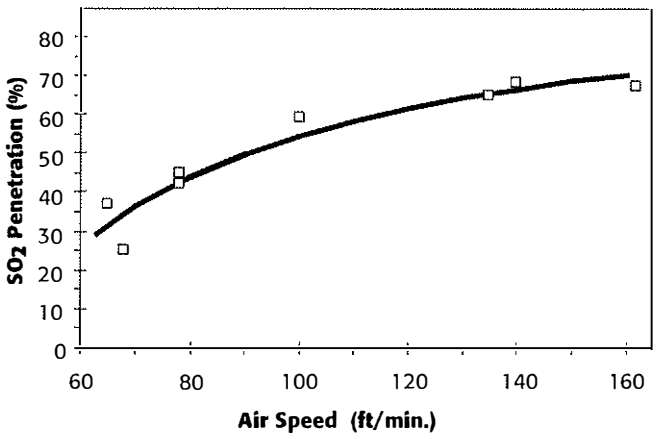


Fig. 8. Air speed past pallets of grape boxes influences the level of SO_2 penetration into center boxes. These test data are from circulating-air fumigation on EPS boxes with paper-wrapped bunches.

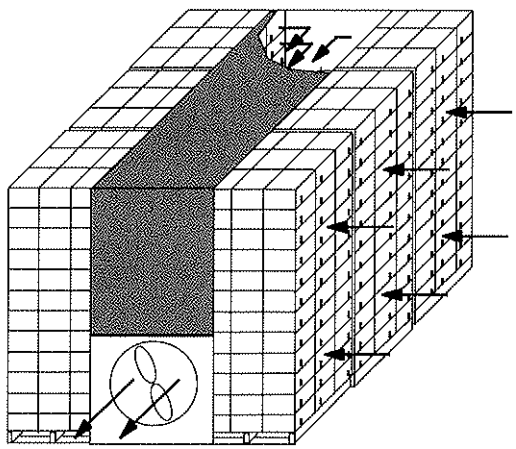


Fig. 9. Tunnel-type forced-air system for cooling and fumigating grapes.

Air flow systems used in forced-air fumigation are the same as those used in forced-air cooling. Forced-air fumigation and cooling may use a "tunnel" system: a reinforced tarp covers the open area between two pallet lanes (fig. 9), and a fan removes air from the space between the pallets, creating a low-pressure area and forcing room air to travel through the boxes and into the space between the pallets. When sulfur dioxide gas is introduced into the room air, it too is forced through the boxes, resulting in penetration levels exceeding 70 percent. Since penetration is rapid and thorough, even bagged or tissue-wrapped fruit can have excellent exposure to the fumigant (fig. 10). A relatively low room CT can result in CTs of more than 100 ppm-hours within the grape package.

The air flow used in many forced-air fumigation rooms is typical of forced-air coolers, about 1 cubic foot of air per minute per pound of product (cfm/lb). Good sulfur dioxide penetration has been observed even in a forced-air cooler with lower air flow and slower cooling times. Some forced-air initial fumigation units run at 0.5 cfm/lb, and appear adequate for sulfur dioxide fumigation.

For initial fumigation, the maximum permitted sulfur dioxide concentration is 10,000 ppm, and a few operators regularly use this level in small circulating-air fumigation chambers. Many operators use 5,000 ppm for initial fumigation. The actual sulfur dioxide levels for a particular facility must be determined by using dosimeter tubes to measure sulfur dioxide penetration into boxes.

The following formula can be used to calculate the amount of sulfur dioxide needed for a traditional fumigation, knowing the room volume in cubic feet and the desired sulfur dioxide concentration in ppm.

$$\text{pounds } SO_2 = \frac{A \times V \times C}{10{,}000{,}000}$$

Where

A = 1.67 at 70°F and 1.82 at 32°F
V = room volume (cubic feet)
C = SO_2 concentration (ppm)

Sulfur dioxide concentration may also be expressed in terms of the percentage of sulfur dioxide in the room atmosphere. One percent sulfur dioxide equals 10,000 ppm; 0.5 percent equals 5,000 ppm.

New fumigation facilities are restricted from releasing any sulfur dioxide into the outside atmosphere, and existing facilities may be prohibited from doing so in the near future. Water scrubbing can remove sulfur dioxide from the room atmosphere without venting. The most effective systems are designed to pass all of the refrigeration return air through a water spray or pad assembly. Water can absorb sulfur dioxide at a rate of 10 pounds of sulfur dioxide per 1,400 gallons of water, if the water is at 32°F (0°C) and becomes completely saturated with the fumigant. At 70°F (21°C), water will absorb only half as much sulfur dioxide.

In practice, the actual amount of water used will be several times the theoretical amount because absorption efficiency drops as water nears saturation with sulfur dioxide. The water cannot be re-used, and must be disposed of. Some operations use portable scrubbers. Sodium or potassium hydroxide can be added to the scrubber water to increase the amount of sulfur dioxide it can absorb. In large storage rooms, portable scrubbers often require long periods of operation to yield adequate reductions in fumigant levels. Their efficiency can be reduced dramatically by sulfite salts if they are not maintained. Plugged nozzles are a common problem.

Traditional storage room fumigation

Grapes are normally fumigated every 7 days to prevent the spread of decay from Botrytis-infected berries. Traditional fumigation in cold-storage rooms is similar to traditional circulating-air initial fumigation. The maximum permitted sulfur dioxide concentration for storage fumigation is 5,000 ppm. Many operators use 2,500 ppm to fumigate filled storage rooms, and lower levels to fumigate partially filled rooms.

Facilities using traditional storage fumigation should consider switching to the total utilization method, since traditional storage fumigation has a number of disadvantages. Large room size, poorly designed air flow systems, and non-uniform placement of grape pallets cause even lower levels of sulfur dioxide penetration and greater variations in sulfur dioxide levels in boxes than in initial fumigation. The short fumigation time results in high sulfur dioxide levels in room air at the end of fumigation, and the excess fumigant must be vented to the outside atmosphere or scrubbed before the room is safe for re-entry.

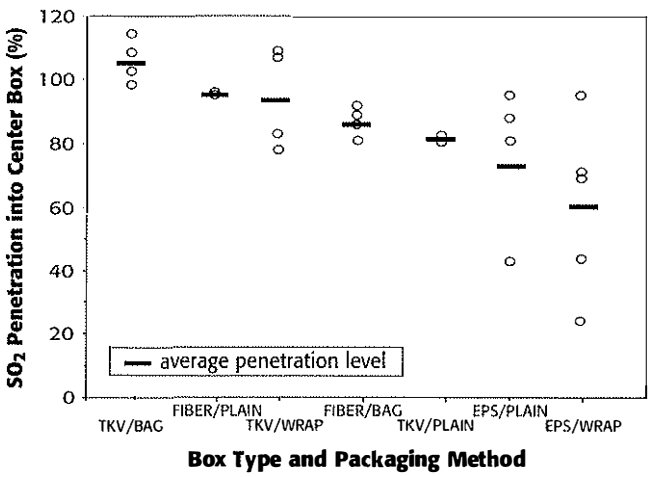


Fig. 10. Sulfur dioxide penetration into the center box of a pallet during forced-air initial fumigation. Penetration was measured as the percentage of SO_2 CT product inside a center box compared with the SO_2 CT product in the air surrounding the pallet.

Total Utilization Fumigation

The total utilization fumigation method differs from the traditional system in that the sulfur dioxide applied is balanced with the amount of sulfur dioxide absorbed by fruit, boxes, and the room itself. Because fumigation is prolonged and the quantity of fumigant is calculated so closely, nearly all of the sulfur dioxide is absorbed by fruit, packaging materials, and room surfaces. At the end of the fumigation period, the sulfur dioxide concentration in the room air is usually less than 2 ppm. If the concentration is above 2 ppm, the dose can be decreased, the fumigation cycle extended, or minimal venting or scrubbing can be used to reduce the sulfur dioxide level to 2 ppm or less.

Total utilization initial fumigation

Initial fumigation under the total utilization system can *only* be used in conjunction with precooling. To allow complete gas absorption by the product and room surfaces, the gas must be kept in contact with the fruit for at least a few hours. Without precooling, grapes would be exposed to a flow of warm air, which would desiccate the stems. Waiting several hours for the sulfur dioxide concentration to drop would also result in an unnecessary delay in cooling. When fumigation and precooling are done simultaneously, the fruit is quickly cooled and effectively fumigated. Forced-air total utilization initial fumigation may use 75 percent less sulfur dioxide than traditional fumigation (as little as 700 ppm), and consistently provides an in-box CT in excess of 100 ppm-hours in all package types. Air flow considerations for traditional initial fumigation also apply to total utilization initial fumigation used with circulating air.

The quantity of sulfur dioxide required for effective decay control can be calculated by multiplying the number of boxes to be fumigated by a factor that depends on the ability of the sulfur dioxide to penetrate the box and packing material. Factors for EPS and TKV boxes are listed in table 3, and appendixes 2 and 3 contain detailed charts describing the amount of sulfur dioxide needed. Each box stored occupies from 2.5 to 3.5 cubic feet of room volume. All calculations are based on a box occupying 3 cubic feet of room volume (10,000 boxes in a 30,000 cu ft room).

Expanded polystyrene boxes (EPS) have lower factors than TKV boxes because polystyrene does not absorb sulfur dioxide as readily as wood and fiberboard materials. There are no reliable industry data on which to base factors for fiberboard boxes, but laboratory studies indicate that they absorb more sulfur dioxide and would have higher factors than TKV boxes. The higher factors ("poor sulfur dioxide penetration" in table 3) should be used for boxes that have low sulfur dioxide penetration rates as a result of poor venting or packing materials that reduce sulfur dioxide movement into the box. Grapes with a high potential for decay may also require high sulfur dioxide levels.

TABLE 3. Factors for determining the amount of SO_2 needed for forced-air fumigation using the total utilization system

Box type*	SO_2 factor (lbs/10,000 boxes†) Good SO_2 penetration	Poor SO_2 penetration
EPS	1.5	3.0
TKV	3.7	6.3

*Fiberboard boxes should probably be fumigated using the higher TKV factors, although there are no industry data available to make a reliable recommendation.
†Factor is based on boxes that weigh 20 to 25 lbs gross.

TABLE 4. Sample calculation of sulfur dioxide needed for an initial forced-air total utilization fumigation (the room holds a maximum of 10,000 boxes of grapes)

Percentage of maximum box storage capacity	Total utilization SO_2 requirement (lbs) EPS box: SO_2 required when gas penetration is good	EPS box: SO_2 required when gas penetration is poor	TKV box: SO_2 required when gas penetration is good	TKV box: SO_2 required when gas penetration is poor
20	0.8	1.5	1.9	3.2
30	0.8	1.5	1.9	3.2
40	0.8	1.5	1.9	3.2
50	0.8	1.5	1.9	3.2
60	0.9	1.8	2.2	3.8
70	1.1	2.1	2.6	4.4
80	1.2	2.4	3.0	5.0
90	1.3	2.7	3.3	5.7
100	1.5	3.0	3.7	6.3

As rooms are emptied of grapes, the sulfur dioxide absorption by room surfaces and coils and air leakage influence the minimum amount of sulfur dioxide needed. Field tests indicate that the amount of sulfur dioxide used should not be less than that required for a half-full room. A sample calculation in table 4 using the factors from table 3 shows the range of sulfur dioxide that could be used for a small forced-air cooling and fumigation room using the developed guidelines. Because initial fumigation rooms may differ in their construction and operation, each room must be calibrated to determine the sulfur dioxide quantity needed to obtain a CT of 100 ppm-hours in packed boxes.

Total utilization storage-room fumigation

Total utilization fumigation is well-suited to grapes that are held in long-term storage. The procedure is similar to that described for total utilization initial forced-air fumigation, except that rather than being forced through the boxes, the sulfur dioxide flows past the outside surfaces of palletized boxes. Lanes of pallets are usually stacked 2 to 3 pallets high with 4 to 6 inches separating lanes.

The amount of sulfur dioxide required for effective decay control is calculated using the same method as for total utilization forced-air fumigation. However, sulfur dioxide penetration into boxes can be much poorer in a storage room than in an initial fumigation room, so the sulfur

TABLE 5. Factors for determining the amount of SO_2 needed for storage-room fumigation

Box type*	SO_2 factor (lbs/10,000 boxes†) Good SO_2 penetration	Poor SO_2 penetration
EPS	3.0	7.5
TKV	6.3	14.0

*Fiberboard boxes should probably be fumigated using the TKV factors, although there are no industry data available upon which to base a reliable recommendation.
†Factor is based on boxes that weigh 20 to 25 lbs gross.

TABLE 6. Sample calculation of SO_2 needed for total utilization fumigation (the storage room holds a maximum of 30,000 boxes of grapes)

Percentage of maximum box storage capacity	Total utilization SO_2 requirement (lbs) EPS box: SO_2 required when gas penetration is good	EPS box: SO_2 required when gas penetration is poor	TKV box: SO_2 required when gas penetration is good	TKV box: SO_2 required when gas penetration is poor
20	4.5	11.3	9.5	21.0
30	4.5	11.3	9.5	21.0
40	4.5	11.3	9.5	21.0
50	4.5	11.3	9.5	21.0
60	5.4	13.5	11.3	25.2
70	6.3	15.8	13.2	29.4
80	7.2	18.0	15.1	33.6
90	8.1	20.3	17.0	37.8
100	9.0	22.5	18.9	42.0

dioxide factors are greater (table 5). The amount of sulfur dioxide should never be below that required for a half-full room. Higher factors should be used for boxes having poor sulfur dioxide penetration characteristics as a result of poor venting, overpacking with fruit, or packing with materials that reduce air movement through the box. Table 6 gives an example of the amount of sulfur dioxide needed for a 30,000-box-capacity storage room, using the table 5 factors. The recommended range of sulfur dioxide amounts for a storage room filled with TKV boxes is shown graphically in figure 11. Figure 12 shows the recommended sulfur dioxide amounts for the same room filled with EPS boxes.

Storage room tests have shown that sulfur dioxide penetration into packed boxes can be very low and extremely variable (fig. 13). Plain-packed EPS and TKV boxes allow the best sulfur dioxide penetration, but their sulfur dioxide levels average only 40 to 50 percent of the room air CT. Wraps and bags further reduce penetration. TKV boxes packed with tissue-wrapped grapes have an average penetration of slightly more than 10 percent. The low levels of sulfur dioxide penetration have been factored into the recommendations for storage-room fumigation.

Still, it is apparent that the differences between various combinations of box and pack may cause some grapes in storage to receive adequate fumigation while others get either too much or too little. Whenever possible, a storage room should contain only boxes with similar sulfur dioxide penetration and box absorption characteristics. For

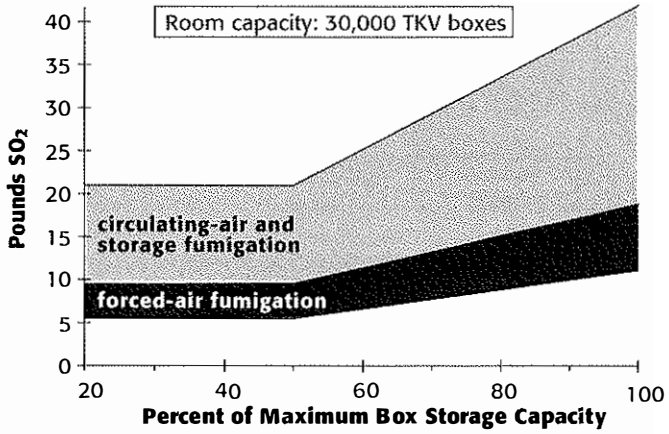


Fig. 11. Example of total-utilization fumigation of TKV boxes. Light-gray area represents the range of SO_2 required for adequate fumigation for circulating-air fumigation; dark-gray area represents the range of SO_2 for forced-air fumigation.

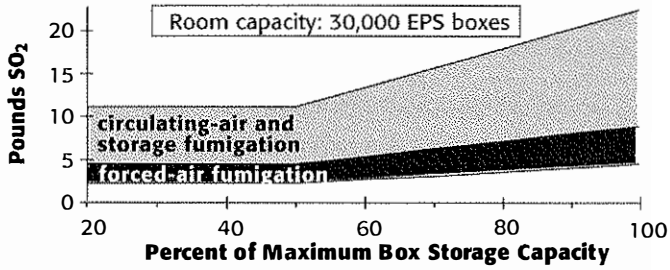


Fig. 12. Example of total-utilization fumigation of EPS boxes. Light-gray area represents the range of SO_2 required for adequate fumigation for circulating-air fumigation; dark-gray area represents the range of SO_2 for forced-air fumigation.

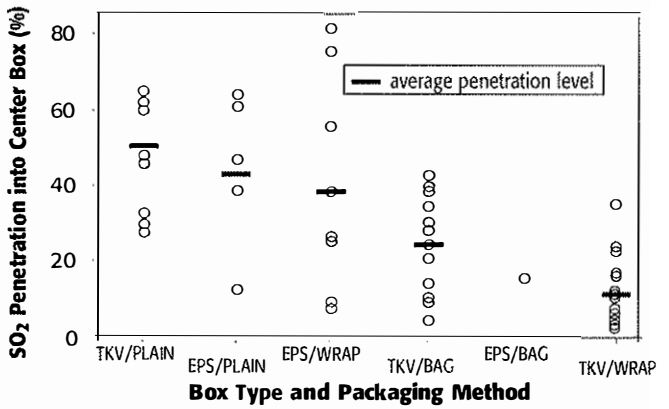


Fig. 13. Sulfur dioxide penetration into the center box of a pallet during a cold-storage fumigation. Penetration was measured as the percentage of SO_2 CT product inside a center box compared with the SO_2 CT product in the air surrounding the pallet.

example, it is best to store EPS and TKV boxes in separate rooms. Similarly, mixing wrapped, plain-pack, and bagged grapes in the same storage room should be avoided whenever possible. Because of the great variability in sulfur dioxide penetration among boxes of the same type, there is still a potential for differences in decay control and residue levels in a room filled with similar boxes.

As with traditional fumigation, a higher air speed past pallets increases sulfur dioxide penetration. Fans should always

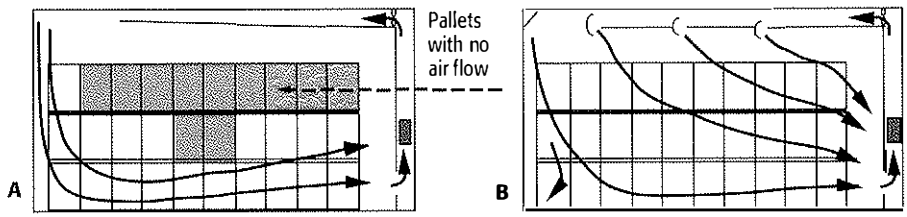
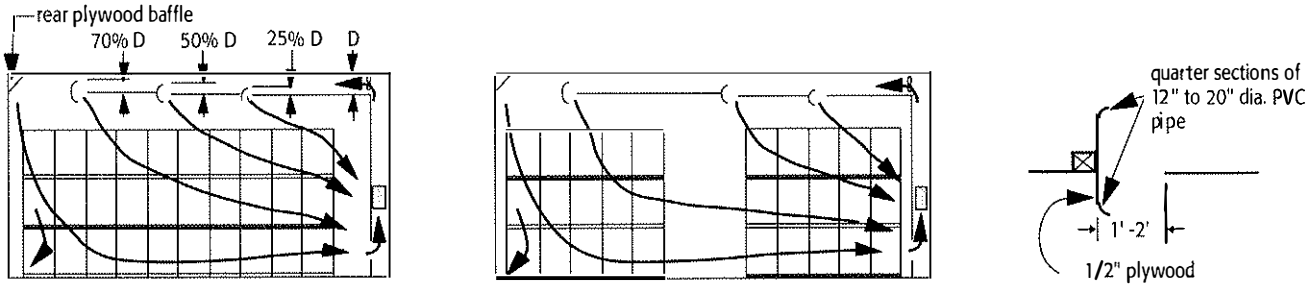


Fig. 14. Air-flow patterns in cold-storage rooms with solid (A) or slotted (B) air supply systems.



A. Cold room with slotted air supply

B. Slot placement for a cold room with a center aisle

C. Detail of vane turn

Fig. 15. Installation recommendations for slotted-ceiling air supply systems.

be on high speed during the first one to two hours of fumigation, and air speeds past all pallets should be greater than 140 feet per minute. Pallets should be stacked neatly with a 4- to 6-inch gap between lanes so that air flow is not blocked.

Non-slotted air ducts or plenums may cause some areas of a storage room to have virtually no air flow. In the storage room shown in figure 14A, about one-third of the pallets received no air flow, particularly those near the top of the storage area. The air flows from the air supply to the back wall, and then down the wall and along the floor to the air return. Cutting slots in the air supply ducts or plenum and installing a baffle at the rear wall can improve air flow uniformity in this room (fig. 14B). The slots must be fitted with turning vanes (fig. 15C). The duct height may be decreased after each slot, since less air has to flow through the ducts after each slot (fig. 15A). Some large cold-storage facilities are designed to have a center aisle as shown in figure 15B. This requires that the distance between the second slot and the duct exit be increased by the width of the aisle.

Pallets stacked three-high in the storage room may have predictable differences in their in-box CTs. In the storage room shown in figure 16, which was completely filled with wrapped, packed grapes in EPS boxes, boxes at the back of the room and closest to the air supply received three to four times more sulfur dioxide than those near the bunker wall. Adding diverters and air openings along the length of the duct can reduce that variability. This consistent difference in box CT has not been detected in large rooms with a center corridor.

As rooms are emptied, entire lanes of pallets may be removed. This practice is not recommended, since it allows air to flow along the open lanes (fig. 17) and partially bypass pallets in other areas. Minimize the number of open lanes in storage rooms, and consolidate the fruit into rooms that are more full.

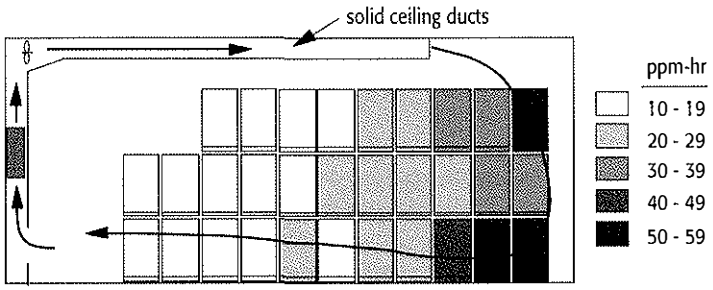


Fig. 16. Sulfur dioxide levels in wrap-packed EPS boxes. Room was full and total utilization fumigation was used.

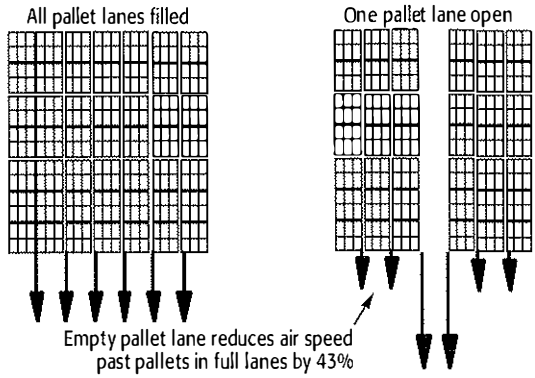


Fig. 17. Empty pallet lanes allow air to bypass the filled pallet lanes.

Sulfur dioxide penetration into individual boxes varies with the individual box's position on the pallet. Top corner boxes can receive almost 60 percent more sulfur dioxide than the center boxes. Sulfur dioxide penetration is related to the number and size of vent holes exposed to the outside surfaces of the pallet (table 7). Pallet designs that allow all boxes to have at least one side exposed to the outside allow more uniform sulfur dioxide penetration than designs that include isolated center boxes. Center boxes, which are the most likely sites for Botrytis rot, are used to monitor the effectiveness of decay-control measures. The top corner boxes are most likely to have high sulfur dioxide exposure, and are used to monitor residues.

Calibration

In all storage rooms, the operator should determine the effectiveness of the fumigation program by conducting CT, residue, and Botrytis-control tests as follows:

CT. A CT of at least 100 ppm-hours should be indicated by dosimeter tubes put among the grapes in boxes located in the hardest-to-fumigate positions in the room – typically, center boxes located in pallets in areas with the least air flow. Dosimeter tubes should be placed in the boxes immediately before fumigation and removed and read at the completion of fumigation. Excessive sulfur dioxide usage is indicated if all of the dosimeter tubes have a color change along their entire length. Appendix 1 summarizes sampling positions.

Residues. Residue analyses should be conducted on grapes removed from the easiest-to-penetrate positions. High residue areas can be located by dosimeter tubes and are typically top corner boxes in the highest air flow areas. Because of the variability of residue analysis, residues in excess of 3 ppm sulfur dioxide should be viewed with concern.

TABLE 7. Effect of position on pallet on the penetration of fumigant into a given box*

Box layer on pallet	Box position on pallet	Number of exposed vent holes	Penetration† (% of room air CT)
top	corner	22	80
bottom	corner	22	72
top	edge	15	72
bottom	edge	15	67
bottom	center	14	62
top	edge	12	59
middle	corner	12	58
top	center	10	61
middle	edge	10	55
middle	edge	2	61
middle	center	0	51

*Total utilization fumigation in cold storage. Dosimeter tubes were placed in centers of 21 lb EPS boxes; grapes were bagged, and pads did not cover vent holes.
†Room air CT = 218 ppm-hours.

Botrytis control. Grapes held in storage for a prolonged period should be inspected for the number of Botrytis-infected berries. Initial fumigation reduces the incidence of Botrytis by killing the spores of this fungus. Fumigated rooms are nearly sterile; living Botrytis spores are not present in the atmosphere in these rooms. Infected berries found later during storage are the result of infections that were initiated in the field. Inadequate fumigation and temperatures above 35°F (1.7°C) during cold storage after the initial fumigation allow mycelial development, and berry-to-berry spread (nesting).

Frequency of storage-room fumigation

Storage rooms should be fumigated frequently enough to control the mycelia from infected berries before the mycelia can spread to adjacent berries. The speed with which mycelium grows varies with temperature. Berry temperature during storage should be as close as possible to 31°F (-0.5°C). Regular sulfur dioxide fumigation is necessary to control the spread of Botrytis from existing infected berries. Considerable experience by industry and recent test results indicate that a fumigation interval of 7 days is adequate for this purpose. A longer interval does not seem desirable. Occasionally, facilities lengthen the fumigation interval to 10 days, but such practices may lead to a greater amount or spread of decay.

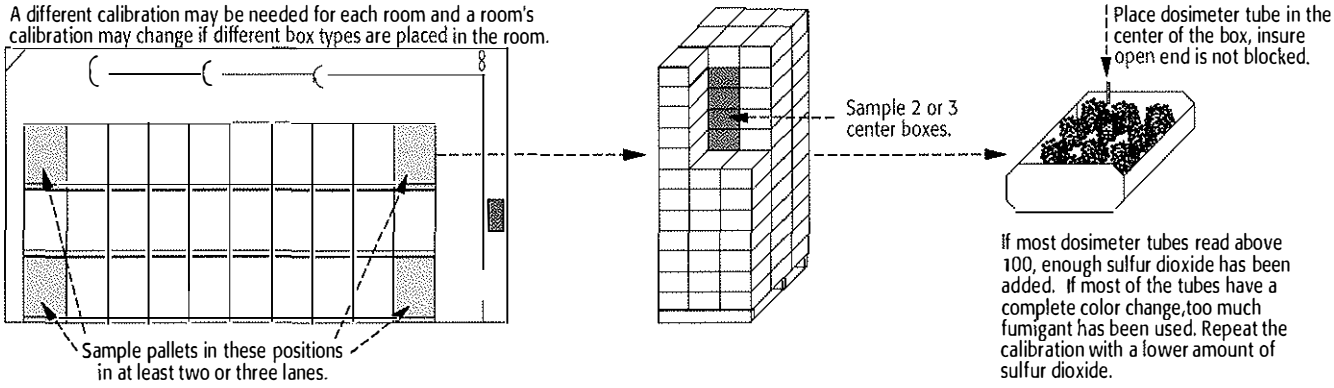
Three-times-per-week variant of total utilization

Before the one-time-per-week total utilization procedure was developed, some operators developed a fumigation procedure based on the use of very low dosages (200 to 400 ppm) of sulfur dioxide applied three times per week. Like total utilization, this system required no venting. This variant of the total utilization procedure appears to give excellent protection against the spread of Botrytis and results in low residues and little berry injury. The method does not seem to be acceptable to most of the industry, since it requires fumigation three times per week. Once-a-week fumigation under the total utilization procedure accomplishes the same objectives.

Facility Maintenance

A successful sulfur dioxide fumigation program requires that the cold-storage facility be properly maintained. Problems such as leaking door seals, inoperative sulfur dioxide input lines, inoperative fans, fans that could not be run at high speed, and poorly constructed or maintained air ducts reduce fumigation effectiveness. To be successful, the storage and fumigation facility must be in good working order.

APPENDIX 1. Sampling Sites for In-Box CT



APPENDIX 2. Fumigation Table for TKV Boxes

This appendix estimates the amount of sulfur dioxide needed as a fumigation starting point.
Start with the lowest amount and determine actual amounts needed for an individual room with dosimeter tubes. Each room will have its own calibration chart. In a room with mixed containers and packs (TKV, EPS, fiberboard), use the rate for the major pack and verify the in-box CT level of sulfur dioxide with dosimeter tubes.

Example:

1. Select storage or forced-air fumigation.
2. Select type of sulfur dioxide penetration into box (good or poor).
3. Select box capacity of room.
4. Select percent room fill.
5. Determine pounds of sulfur dioxide needed from corresponding column. Example: TKV box, storage fumigation, 60,000-box room capacity, good sulfur dioxide penetration, 75% full, order 29 pounds of sulfur dioxide.

Note: Under the total utilization method, room-air SO_2 concentration is usually 20-30 ppm after 2 hours. Concentrations that are higher than 30 ppm after 2 hours indicate that the SO_2 dose is too high.

	TKV STORAGE						TKV FORCED AIR					
				USE WITH EXTREME CAUTION						USE ONLY WITH CALIBRATION		
ROOM CAPACITY IN BOXES	GOOD PENETRATION % ROOM FILL			POOR PENETRATION % ROOM FILL			GOOD PENETRATION % ROOM FILL			POOR PENETRATION % ROOM FILL		
	50% or Less	75%	100%	50% or Less	75%	100%	50% or Less	75%	100%	50% or Less	75%	100%
100,000	32	47	63	70	105	140	19	28	37	32	47	63
95,000	30	45	60	67	100	133	18	26	35	30	45	60
90,000	29	43	57	63	95	126	17	25	33	29	43	57
85,000	27	41	54	60	89	119	16	23	31	27	41	54
80,000	25	38	50	56	84	112	15	23	30	25	38	50
75,000	24	35	47	53	79	105	14	21	28	24	35	47
70,000	22	33	44	49	74	98	13	20	26	22	33	44
65,000	21	31	41	46	68	91	12	18	24	21	31	41
60,000	19	29	38	42	63	84	11	17	22	19	29	38
55,000	18	26	35	39	58	77	10	15	20	18	26	35
50,000	16	24	32	35	53	70	10	14	19	16	24	32
45,000	14	21	28	32	47	63	9	13	17	14	21	28
40,000	13	19	25	28	42	56	8	11	15	13	19	25
35,000	11	17	22	25	37	49	7	10	13	11	17	22
30,000	11	16	21	21	32	42	6	8	11	10	14	19
25,000	10	14	19	18	26	35	5	7	9	8	12	16
20,000	7	10	13	14	21	28	4	5	7	7	10	13
15,000	5	7	9	11	16	21	3	5	6	5	7	9
10,000	3	5	6	7	11	14	2	3	4	3	5	6
5,000	2	2	3	4	5	7	1	2	2	2	2	3
	50% or less	75%	100%	50% or less	75%	100%	50% or less	75%	100%	50% or less	75%	100%
	% ROOM FILL			% ROOM FILL			% ROOM FILL			% ROOM FILL		
	Pounds sulfur dioxide											

APPENDIX 3. Fumigation Table for EPS Boxes

This appendix estimates the amount of sulfur dioxide needed as a fumigation starting point.
Start with the lowest amount and determine actual amounts needed for an individual room with dosimeter tubes. Each room will have its own calibration chart. In a room with mixed containers and packs (TKV, EPS, fiberboard), use the rate for the major pack and verify the in-box CT level of sulfur dioxide with dosimeter tubes.

Example:

1. Select storage or forced-air fumigation.
2. Select type of sulfur dioxide penetration into box (good or poor).
3. Select box capacity of room.
4. Select percent room fill.
5. Determine pounds of sulfur dioxide needed from corresponding column. Example: EPS box, storage fumigation, 60,000-box room capacity, good sulfur dioxide penetration, 75% full, order 14 pounds of sulfur dioxide.

Note: Under the total utilization method, room-air SO_2 concentration is usually 20-30 ppm after 2 hours. Concentrations that are higher than 30 ppm after 2 hours indicate that the SO_2 dose is too high.

	EPS STORAGE						EPS FORCED AIR					
	GOOD PENETRATION			USE WITH EXTREME CAUTION POOR PENETRATION			GOOD PENETRATION			USE ONLY WITH CALIBRATION POOR PENETRATION		
ROOM CAPACITY IN BOXES	% ROOM FILL			% ROOM FILL			% ROOM FILL			% ROOM FILL		
	50% or Less	75%	100%	50% or Less	75%	100%	50% or Less	75%	100%	50% or Less	75%	100%
100,000	15	23	30	38	56	75	8	11	15	15	23	30
95,000	15	22	29	36	53	71	7	11	14	15	22	29
90,000	14	20	27	34	51	68	7	11	14	14	20	27
85,000	13	20	26	47	71	94	7	10	13	13	20	26
80,000	12	18	24	30	45	60	6	9	12	12	18	24
75,000	12	17	23	28	42	56	6	8	11	12	17	23
70,000	11	16	21	27	40	53	6	8	11	11	16	21
65,000	10	15	20	25	37	49	5	8	10	10	15	20
60,000	9	14	18	23	34	45	5	7	9	9	14	18
55,000	9	13	17	21	31	41	4	6	8	9	13	17
50,000	8	11	15	19	29	38	4	6	8	8	11	15
45,000	7	11	14	17	26	34	4	5	7	7	11	14
40,000	6	9	12	15	23	30	3	5	6	6	9	12
35,000	6	8	11	13	20	26	3	4	5	6	8	11
30,000	5	7	9	12	17	23	3	4	5	5	7	9
25,000	4	6	8	10	14	19	2	3	4	4	6	8
20,000	3	5	6	8	11	15	2	2	3	3	5	6
15,000	3	4	5	6	8	11	1	2	2	3	4	5
10,000	2	2	3	4	6	8	1	2	2	2	2	3
5,000	1	2	2	2	3	4	1	1	1	1	2	2
	50% or less	75%	100%	50% or less	75%	100%	50% or less	75%	100%	50% or less	75%	100%
	% ROOM FILL			% ROOM FILL			% ROOM FILL			% ROOM FILL		
	Pounds sulfur dioxide											

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