Executive Summary

With only a few exceptions, most mango fruit are grown in areas of the world where various fruit fly species are established. For this reason, export of these mango fruit into the United States has required phytosanitary measures, usually a quarantine treatment, to assure no live fruit fly insects are present in imported fruit.

The quality of mango fruit on the markets in the United States is too frequently of substandard quality. While it is recognized that many factors can contribute to a loss in fruit quality; many in the mango industry feel that the hot water protocol is mainly responsible for the loss in mango fruit quality.

Other treatment alternatives are currently available to the industry, including forced hot air and irradiation, while other options are under development and could become available either in the near or distant future. This report presents a description of the various treatment options for mango fruit and the advantages and disadvantages of each potential alternative to the hot water protocol. In addition, a thorough evaluation of the hot water protocol and mango handling at the packinghouse level is presented with recommendations for improvements.

Among the various alternatives, forced hot-air, forced hot-air with controlled atmospheres (high temperature controlled atmospheres) and irradiation show the most promise for improvements to fruit quality and each could be implemented in a relatively short time frame. The high temperature controlled atmosphere treatment is not yet approved by APHIS, but APHIS recently approved this treatment for use within the U.S. Each of these options is capital intensive, especially the irradiation option. For this reason, we recommend that the industry pursue improvements to the hot water protocol and fruit temperature management before and after the hot water treatment in addition to exploring alternative treatments.

Alternative Treatments to Hot Water Immersion for Mango Fruit

Report to the National Mango Board

December 2008 (*Revised February 2009*)

Dr. Elizabeth Mitcham, Dept. Plant Sciences, University of California, Davis, CA, USA

Dr. Elhadi Yahia, Facultad de Ciencias Naturales, Universidad Autonoma de Queretaro, Mexico

Introduction

With only a few exceptions, most mango fruit are grown in areas of the world where various fruit fly species are established. For this reason, export of these mango fruit into the United States has required phytosanitary measures, usually a quarantine treatment, to assure no live fruit fly insects are present in imported fruit. The hot water treatment protocols for mangoes from Central and South America were developed in the early 1990s. More than 100 hot water treatment facilities have been installed in Central and South America for treatment of mango fruit and these facilities have been gradually improved over the many years of operation.

The quality of mango fruit on the markets in the United States is too frequently of substandard quality. While it is recognized that many factors can contribute to a loss in fruit quality. Many in the mango industry feel that the hot water protocol is mainly responsible for the loss in mango fruit quality.

Other treatment alternatives are currently available to the industry, including forced hot air and irradiation, while other options are under development and could become available either in the near or distant future. This report presents a description of the various treatment options for mango fruit and the advantages and disadvantages of each potential alternative to the hot water protocol. In addition, a thorough evaluation of the hot water protocol and mango handling at the packinghouse level is presented with recommendations for improvements. The information presented in this report was collected from referred journal publications, popular press articles, through interviews with mango packers, researchers, and APHIS representatives, and through site visits to mango packing facilities.

Hot Water Treatment

Hot water immersion is an efficient treatment to disinfest mango fruit of fruit flies and is the most common quarantine heat treatment in use today due to the volume of mango fruit from Latin America that are treated. The USDA Animal and Plant Health Inspection Service (APHIS) approved the hot water immersion quarantine treatment for Tephritidae fruit flies in mangoes in 1987. Hot water treatments have been used by growers in several countries as quarantine treatments for mango and papaya fruits. Large commercial hot water treatment facilities are routinely used to treat mangoes with hot water immersion at a temperature of 115 to 116ºF (46.1 to 46.5ºC) for 65 to 110 minutes, depending on fruit weight and variety for export to the U.S. There are approximately 75 hot water treatment facilities in Mexico, 5 in Ecuador, 6 in Guatemala, 11 in Peru and 10 in Brazil.

Hot Water Treatment Requirements

According to USDA APHIS requirements, for rounded varieties (Tommy Atkins, Kent, Haden, Keitt), the treatment for fruit flies requires heating in 115ºF (46.1ºC) water for 75 to 110 minutes, depending on the weight of the mango. Fruit up to 500g are treated for 75 minutes, fruit weighing 501 to 700g are treated for 90 minutes and mangoes 701 to 900g (only approved for Mexico and Central America) are treated for 110 minutes. For flat, elongated varieties (Frances, Ataulfo, Manila), fruit up to 375 grams are heated 65 minutes and fruit 375 to 570 grams are heated for 75 minutes. There are specific requirements for the water temperature during the first few minutes of treatment, and the hot water system must be certified each year before it is first used.

Hydro-cooling (Fig. 1C,D) is now allowed immediately following the hot water treatment if 10 minutes is added to the heat treatment time, or fruit may be hydro-cooled after a waiting period of at least 30 minutes at ambient temperature. The hydro-cooler water must be no colder than 70ºF (21.1ºC), according to APHIS.

Figure 1. Hot Water Treatment Facilities for Mango

A

B

C

D

E

F

Many mango packing houses have installed hot water treatment facilities. These generally consist of a series of hot water tanks, a rack system for loading of field bins filled with mangoes, and a crane for loading and unloading the racks into the hot water (see Figure 1A,B). The systems seem to be functioning smoothly once they are approved for use at the start of the season.

Although hydro-cooler water temperatures as low as 70ºF (21.1ºC) are allowed by APHIS, many of the facilities we or the Mango Supply Chain Project Team have visited were either not hydro-cooling many of their fruit, were using water many degrees above 70ºF (80º to 89ºF, 26.7-31.7ºC), and/or were hydro-cooling for an insufficient length of time (in some cases for less than 10 minutes) (Table 1). The maximum time observed was 30 minutes and the shortest time was 2 minutes. At some facilities, the timing for hydro-cooling appeared to be random and was not driven by the need to add a new rack of fruit from the hot water tank and therefore limited cooling capacity. However, many of the facilities do not have sufficient capacity to hydro-cool all of the heated fruit. Because of the warm temperatures of the hydro-cooler water, in some cases the fruit only cooled to an internal pulp temperature of 98 (36.7ºC) to 108°F (42.2ºC) before removal from the hydro-cooler (Table 1).

When fruit had been hydro-cooled, they were often packed within 1½ hours, but when they were not hydro-cooled, they were packed after 12-24 hours. The reason is that the packer is waiting to see if damage will develop on the fruit that was not hydro-cooled (on the surface, perhaps from latex on the skin). There is usually no cooling of fruit before packing and sometimes not any cooling after packing and before shipment. Some sheds only cool fruit going to certain markets, such as Japan, or for certain customers. Hydro-cooling mango fruit after hot water treatment decreases the pulp temperature much more rapidly (Shellie and Mangan, 2002; Fig. 2) and has been demonstrated to slow the metabolic rate of the fruit (de Leon et al., 1997). Hot water treatment has been shown to expand the fruit cuticle (waxy layer) causing isolated fissures and enlarged pores as seen under an electron microscope, and the appearance of the cuticle returned to normal after hydro-cooling (de Leon et al., 1997). Hot water treatment immersion is not effective as a quarantine treatment to disinfest mangoes of the mango seed weevil. Weevils in ‘Alfonso’ mangoes from India were not killed when infested mango fruit were immersed in water at 118.4-125.6ºF (48-52ºC) for up to 90 min, and 129-158ºF (54-70ºC) for up to 5 min (Shukla and Tandon, 1985).

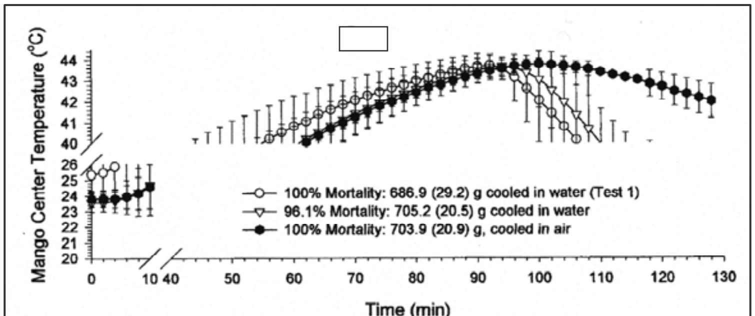

Figure 2. Average temperature at center of mango fruit during 90 min immersion in 41°C water and cooling in 22 to 26.5°C water (open symbols) or 23°C open air (closed symbols).

Mango Tolerance to Hot Water

Hot water immersion can damage the quality of mango fruit (Yahia and Campos, 2000). Small fruit are generally damaged more readily by heat compared to large fruit, in part because they heat more quickly. Grading by weight/size before heat treatments is required, with shorter treatment times for smaller fruit. Paull and Armstrong (1994) reported that the temperature and immersion time affects potential damage of mango fruit such as skin scalding, lenticel spotting, and retention of unripe starchy areas in mango flesh (stem end cavity). The damages vary by cultivar. Some of the factors that have been shown to reduce fruit injury by heat include delaying treatment for 24 hrs after harvest, and treatment of more mature fruit (Esguerra and Lizada, 1990; Esguerra et al., 1990; Jacobi and Wong, 1990; Jacobi et al., 1994; 1995).

Peru,, Ecuador, Mexico,

Table 1. Hydro-cooling practices for mangoes treated with the hot water protocol as observed on our site visit and by the Mango Supply Chain Team in 2007-08.

	Ecuador	Guatemala	Mexico	Peru
Method	a – spray with hose b – none used c - immersion	a – immersion b – none used c – none used d – none used e - immersion	a – immersion b – immersion c – immersion d - immersion e – none f – none g – immersion h – immersion i – immersion j – immersion k – immersion l – immersion	a – immersion b – none used c – immersion d – none used e – none used f - immersion
Delay before hydrocooling or immediate hydrocooling? (where hydrocooling is used)	a – 30 min b – no c – 30 min	a – 0 min (add 10 min to heat) e – 30 min	a – 0 min b – 0 min c – 0 min d – 0 min e – no hydro-cooling (they leave the fruit at ambient for about 8 hrs) f – no hydro-cooling (they leave the fruit at ambient overnight) g – 0 min h – 0 min i - 0 min j – 0 min k – 30 min l - 30 min	a – 30 min c - 2 min f – 30 min

	Ecuador	Guatemala	Mexico	Peru
Length	a – 5 min c – 10 min	a – 16 min e – 20 min	a – 20 min b – 30 min c – 10 min d – 30 min g – 4-10 min h – 16 min i – 10 min j – 30 min k – 15-20 min l – 30 min	
Water Temp.		a – 81ºF (27°C) e – 71ºF (21.7°C)	a – 86ºF (30ºC) b – 72ºF (22ºC) c – 77ºF (25ºC) d – 91.4ºF (33ºC) g – 79-80ºF (26-27ºC) h – 89ºF (31.7ºC) i – 85.5ºF (30ºC) j – 77ºF (25ºC) k – 78ºF (25.5ºC) l – 84ºC (29ºC)	a – 72-84ºF (22-29ºC) f – 70ºF (21ºC)

	Ecuador	Guatemala	Mexico	Peru
Final Pulp Temp. after 1 hour	a – 102ºF (39ºC) b – 112ºF (44.5ºC) c – 98ºF (36.7ºC)		a – 95.6ºF (35.3ºC) b – 94-96ºF (9434.4-35.6ºC) c – 91.4ºF (33ºC) d – 105.6ºF (40.9ºC) e – (pulp temp of packed fruit 90ºF, 32ºC) g – 107-116ºF (42-47ºC) h – 108ºF (42ºC) i – 102ºF (39ºC) j - 88-89.6ºF (32-33ºC) k – 91.4-96ºF (33-35ºC) l – 92-102ºF (33-39ºC)	
Cooling before Shipping	a – room cooling at 53ºF (11.8ºC) b – forced-air for 1 to 2 h at 48.6ºF (9.2ºC) c – forced-air cooling 4 to 6 h at 50.9ºF (10.5ºC)	a – room cooling 3 h at 48.9ºF (9.4ºC) b – room cooling 6 h at 52.3ºF (11.3ºC) c – forced-air for 5-6 h at 53.7ºF (12.1ºC) d – room cooling for 5 h at 50.2ºF (10.1ºC) e - cold room at 54.8ºF (12.7ºC)	a – room cooling at 59ºF (15ºC) b – room cooling at 58ºF (14.5ºC) c – room cooling at 59-61ºF (15-16ºC) (they have forced-air cooling unit but rarely used) d – forced-air cooling at 50ºF (10ºC) for 4-6 h e – room cooling at 58ºF (14.4ºC)	a – forced-air 5 h at 50.8ºF (10.5ºC) b – none c –none d – forced-air 6-7h at 48.9ºF (9.4ºC) e – forced-air 8h at 53.6ºF (12ºC) f – forced-air 9h at 47.8ºF (8.8ºC)

	Ecuador	Guatemala	Mexico	Peru
Cooling before Shipping, cont.			f – room cooling at 60ºF (15.4ºC) g – no cooling, they have a cold room but not always used. h – room cooling at 61ºF (16ºC), but not commonly used. i – room cooling at 61ºF (16ºC) j – room cooling at 55-61ºF (13-16ºC) k – room cooing at 62.6ºF (17ºC), they have forced-air 5 h at 50ºF (10CF) but only used when distributor requests it l – room cooling at 54.3ºF (12.4ºC). They have 2 forced-air tunnels but they do not seem to use it often	

Spalding et al. (1988) reported that immersion in hot water (115ºF (46ºC) for 60-90 min, followed by storage for 3 days at 55.4ºF (13ºC) and ripening at 75ºF (24ºC)) did not damage the market quality (ripening time, pH, total titratable acidity, ascorbic acid, soluble solids content) of ‘Tommy Atkins’ or ‘Keitt’ mangoes. However, lenticels were darker on ‘Tommy Atkins’ fruit immersed in water at 115ºF (46ºC) for 120 min, on ‘Keitt’ immersed in water for 90 min at 115ºF (46ºC), and on both cultivars immersed for 60 min at 120ºF (49ºC). Anthracnose decay was reduced in ‘Keitt’, and stem-end rot, caused by *Diplodia natalensis* or *Phomopsis citri*, was reduced on both cultivars immersed in water at 115 or 120ºF (46ºC or 49ºC). Immersion of ‘Oro’ mangoes for 75 min at 115ºF (46.1ºC) caused no fruit damage (Sharp et al., 1989a). ‘Kent’, ‘Tommy Atkins’ and ‘Keitt’ mangoes immersed for 90 min and then refrigerated at 52ºF (11.1ºC) for 7, 11 or 14 days were not damaged. ‘Haden’ mangoes immersed for 90 min at 115ºF (46ºC) and then held at 75ºF (24ºC) were acceptable (Sharp et al., 1989a). Treatment of softening ‘Ataulfo’ mangoes with 115ºF (46ºC) water for 75 to 90 minutes did not cause visible damage, but fruit needed to be stored at 52ºF (11.1ºC) after treatment to slow ripening to allow time for marketing before ripening (Sharp et al., 1989b).

Hydro-cooler water must be properly sanitized with chlorine or other sanitizers to prevent the possible spread of human pathogens such as *Salmonella enterica* as was observed in 2000, sickening 15 people and killing 2 (Sivapalasingam et al., 2003). In the described example, the initial source of water used for the hydro-cooler was found to be contaminated with *Salmonella* and *E. coli* species. When hot water treated fruit are placed into the cool hydro-cooler water, cool water can be pulled inside the fruit, internalizing contamination if present in the water.

Improving Fruit Tolerance to the Hot Water Protocol

A number of steps can be taken to improve the hot water treatment process and therefore improve the overall quality of mango fruit on the market in the U.S. Before the mango industry considers switching to an alternative strategy for quarantine treatment, even a non-treatment option, improvements to the current procedures should be seriously considered. Mango fruit quality issues are often blamed on the hot water treatment protocol, but it is our opinion that if fruit handling before and after the hot water treatment is optimized, this treatment could have minimal effects on fruit quality. It is clear that there are a number of opportunities to greatly improve mango fruit quality with some simple changes to procedures, some investment in infrastructure, and more attention to details. Many of these steps can be easily implemented, but some would require more effort.

There is a lot of variability among the various packinghouses and even within operations as to how fruit are handled. Some of the problems that have been observed include delays in fruit receiving at high temperatures in the sun, little to no sorting of fruit for defects or maturity before or after the hot water treatment, elevated temperatures above the required set-point during hot water treatment in some cases, highly inconsistent hydro-cooling after hot water treatment (duration, water temperature), delays to packing the fruit at high ambient temperatures, rough handling during packing, inconsistent and unsophisticated wax application methods, poor packaging materials leading to box collapse and pallet instability, little to no cooling of fruit after packing, and inconsistent cooling of transportation vehicles prior to loading.

The hot water process could be improved by taking the following steps:

1. Assure fruit are mature prior to treatment, as immature fruit are more susceptible to damage by hot water
2. Avoid latex contact with fruit surface during harvest – damage can be exacerbated by hot water
3. Improve temperature control in hot water tanks where needed to allow treatment at the lowest allowable temperature. Even one degree above the required temperature can make a difference in fruit tolerance
4. Always hydro-cool fruit immediately after heat treatment (after adding the additional 10 minutes to the hot water protocol), or after the 30 minute delay following hot water treatment, whether fruit is to be packed immediately or

5. Hydro-cooling should be for a sufficient length of time to reach a temperature of 80 to 85ºF (27 to 29.4ºC) center pulp temperature (will depend on fruit weight, but likely be closer to 30^{+} minutes). Providing water circulation within the hydro-cooler tank will speed the cooling process
6. Maintain hydro-cooler water bath at 70 to 72°F (21-22.2) with sufficient cooling capacity (condenser) to remove heat from mangoes given the volume of fruit to be hydro-cooled.
7. Maintain sanitizer levels in the hydro-cooler water to maintain effective levels of free chlorine (50 to 100ppm Chlorine) or oxidation reduction potential (ORP) of 650 to 700 mV (Suslow, 2004)
8. Pack fruit as soon as possible after hydro-cooling. If it is necessary to hold the fruit for 12 hrs after cooling and before packing, at least 8 inches of space should be provided between the stacks of bins (Fig. 1E,F) and ventilation (overhead paddle fans) or some other means of reducing the temperature around the fruit should be used.
9. Pre-cool the fruit again using forced-air cooling immediately after packing and before placing into cold storage or cold container. Pallets should be arranged to restrict air flow so it can only move through the fruit boxes to the fan. Air temperature during forced-air cooling should be 48 to 50ºF (9 to 10ºC).
10. Place fruit into a cold room after packing if not immediately into refrigerated truck. If fruit need to wait before shipping, it should always be in the cold room at temperatures from 50 to 60ºF (10 to 15ºC).
11. Transport containers should always be precooled before loading (to a temperature no higher than 54ºF (12ºC)), and warm fruit should not be loaded into the cold container.
12. Conduct research to determine whether a lower hydro-cooler temperature might still provide for complete fruit fly control with either the 30 minute delay or the additional 10 minutes of hot water treatment time. A temperature closer to 50ºF (10ºC) would provide more rapid hydro-cooling, thereby speeding the process.

POSSIBLE ALTERNATIVES TO HOT WATER TREATMENT

Vapor Heat or Forced-Hot Air

For mangoes shipped to the U.S. from Latin America, hot water treatment is by far the most common quarantine treatment. However, around the world, there is widespread use of forced hot-air and vapor heat treatments for mango fruit (Table 2). While hot water immersion quarantine treatments are relatively easy to engineer, forced hot-air and vapor heat treatment equipment requires more engineering and somewhat more complex computer programs to operate and monitor the treatment parameters and equipment.

Vapor Heat Treatment (VHT)

Vapor heat, the oldest of the three methods of quarantine heat treatment, consists of heating the host fruit by moving hot air saturated with water vapor over the fruit surface. Vapor heat treatment (VHT) is a high humidity air treatment. When the mango is at dew point temperature or lower temperature, the air will condense on the fruit surface and the condensate will conduct heat energy from the surface into the center of fruit flesh. Heat is transferred from the air to the commodity by condensation of the water vapor (heat of condensation) on the relatively cooler fruit surface (Armstrong and Mangan, 2007). Fruit may be heated over time to a target temperature which may be the end of the heat treatment, or fruit may be held for a specific time (holding time) that is required to kill the insect pests. Treatments usually take 3 to 4 hours from start to end of heating.

One of the first uses of vapor heat was in Mexico in 1913 to control the Mexican fruit fly (Hansen and Johnson, 2007). Vapor heat treatment is used for mangoes exported from Australia, Thailand, The Philippines and Taiwan, particularly for the Japanese market (Table 2). An old vapor heat treatment for ‘Manila’ mangoes from Mexico is still on the approved list, but requires a 6 hour hold time at a core temperature of 43.3°C. This treatment is not commercially used.

Forced Hot-Air Heating Treatment (FHAT)

Forced hot-air, also known as high-temperature forced air, is a modification of the vapor heat treatment developed by Armstrong et al. (1989) to kill Mediterranean fruit fly, melon fly and oriental fruit fly eggs and larvae in papaya. It is essentially the same as vapor heat except that the fruit surfaces are dry during forced hot-air treatment. Improvements in temperature and moisture monitoring and air delivery have advanced forced hot-air treatments (Hallman and Armstrong, 1994), leading forced hot-air treatments to be developed for commodities previously treated with vapor heat and also being developed for new commodities (Hansen and Johnson, 2007). Forced hot-air treatment appears to be as effective in controlling internal pests as vapor heat, and provides better fruit quality (Laidlaw et al., 1996), becoming the treatment of choice for many fruit previously treated with vapor heat. The fruit skin temperature remains cooler during forced hot air treatments than during vapor heat treatment while the tissue just below the skin heats to lethal temperatures because of the occurrence of evaporative cooling on the fruit surface during forced hot air treatment at lower relative humidity (See Figure 3; Shellie and Mangan, 2000). Forced hot air is the second most common method of quarantine heat treatment, and has been used in the Cook Islands and Fiji and more recently is expanding to the Pacific Basin and Pacific Rim (Table 2). Forced hot air heat treatment is regularly used to treat papayas in Hawaii for shipment to the U.S. mainland with good success.

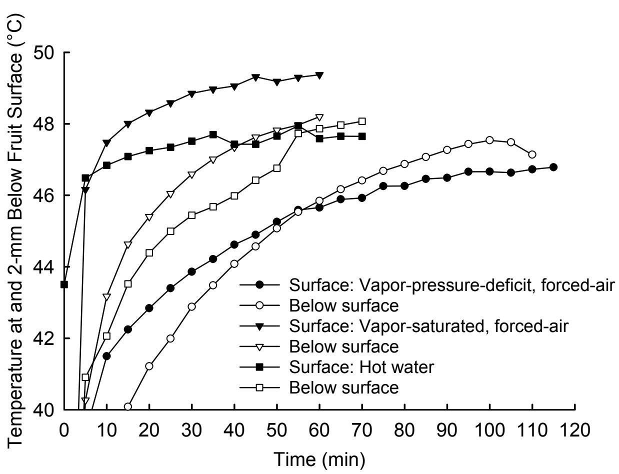

Figure 3. Average temperature at fruit surface (solid symbols) and 2 mm below surface (open symbols) during heating at 48°C via vapour pressure-deficit, forced air (circles), vapour-saturated air (triangles) and hot water (squares). Values represent the average of 12 fruit (grapefruit, orange, papaya and mango) over four treatment replications (from Shellie and Mangan, 2000).

In Mexico, there are four forced hot air units in Michoacan (Fig. 4), Nuevo Leon and Yucatan, that were all designed by the same individual specifically to treat citrus (mostly grapefruits). All utilize steam heat. In Hawaii, fruit are treated in large field bins with mesh bottoms (Fig. 5). In Michoacan, some units have been used to treat mango. The fruit are placed in field totes and loaded into metal racks with openings at the bottom to allow air to enter the bottom of the rack and travel up through the fruit and out the top. The air-flow can be reversed half-way through the treatment to increase heating uniformity within the rack of fruit. The users reported that uniformity of heating within the load is pretty good, but frequently one or two sensors will not read the same as the others. Often it is found that the temperature probe was not working or was not properly inserted in the fruit. If this happens with more than one sensor, the entire load must be retreated. As with all quarantine treatment facilities,

Figure 4. Forced Hot Air Chamber in Mexico used for Citrus Quarantine Treatment

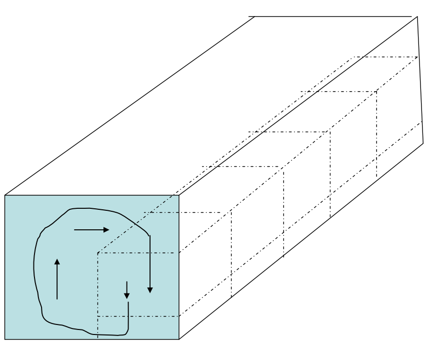

Figure 5. Schematic of a Forced Hot Air Chamber with Bins of Fruit

Figure 6. Forced Hot Air Chamber by Sanshu Sangyo Co., LTD of Japan.

they must be certified at the start of each season. For forced-hot air, this requires a thermal mapping of the chamber and the results determine the location of temperature probes for each treatment run. In Mexico, USDA APHIS had been requiring 40 sensors to be used during the thermal mapping of the chamber to measure fruit temperatures in regular positions throughout the load at the start of the season. However, in 2008, the number of probes required for the thermal mapping exercise was increased to 80.

Companies that have manufactured forced hot-air or vapor heat treatment equipment include FoodPro International (San Jose, Calif. USA; www.foodpro.net), Commercial Dehydrator Systems Inc. (Eugene, Oregon, USA; www.dryer.com), Techi Systems Inc. (Chelan, Washington, USA; www.techni-systems.com) Sanshu Sangyo (Kagoshima, Japan; see Fig. 6; info@sanchu.co.jp) and Takenaka Komuten (Tokyo, Japan; www.takenaka.co.jp). These treatment facilities are relatively expensive (US$120,000 for 8 ton capacity per load) (Armstrong and Mangan, 2007). According to Armstrong and Mangan (2007), hot water immersion equipment costs about one-third that of forced hot-air equipment to treat the same quantity of fruit based on operational costs. An important consideration in the cost of quarantine treatment equipment is the amount of commodity treated, or throughput. The more throughput, the lower the treatment costs. In Hawaii, the cost for forced hot-air or vapor heat treatment of papaya ranges from US$0.17 to US$0.31 per pound (0.45 kg) of treated fruit. Other cost factors include facilities, labor, refrigeration, power and shipping (Armstrong and Mangan, 2007). The various cultivars of mango receive different conditions for internal heating temperature and time because of their unlike size and shape.

High Temperature Controlled Atmospheres (CATTS)

This treatment combines the stress of heat with that of atmospheric stress (referred to as modified atmosphere, MA, or controlled atmosphere, CA) due to reduced oxygen and/or elevated carbon dioxide concentrations (Neven and Mitcham, 1996). Reduced

Table 2. Use of forced hot-air and vapor heat treatments around the world for mango fruit.

Exporting Country	Importing Country	Treatment and parameters
Australia	Japan	Vapor heat to 116.6°F (47°C) core temperature, 15 min hold (‘Kensington’ mangoes)
Cook Islands	New Zealand	Forced hot-air to center temperature 117°F (47.2ºC), 20 min hold period (only used commercially for papayas)
Fiji	New Zealand, Australia	Forced-hot air to center temp. 117°F (47.2ºC), 20 min holding period
Mexico	USA	Forced hot-air to center temp. of 118.4°F (48ºC), 2 min hold
New Caledonia	New Zealand	Forced hot-air to center temp. of 116.6°F (47ºC), 20 min hold period
Philippines	Australia, USA, Japan, New Zealand, Korea	Vapor heat with 115°F (46°C), 10 minute hold (‘Carabao’ mango)
Taiwan	USA	Vapor heat to center temperature of 116°F (46.5°C), 30 min hold period (‘Irwin’ and ‘Haden’ mangoes)
Thailand	Japan	Vapor heat to center temperature of 116°F (46.5°C), 10 min hold period (‘Nang Klang Wun’ mangoe) Vapor heat to 116.6°F (47°C) core temperature, 10 min hold (‘Nam Doc Mai’, ‘Pimsen Dang’, ‘Rad’ mangoes)
Tonga	New Zealand	Forced hot-air to center temp. of 117°F (47.2ºC), 20 min hold period
USA (Hawaii)	New Zealand, USA (Mainland)	Forced hot-air to center temperature of 117°F (47.2ºC) in >4 hours

Adapted from Armstrong and Mangan (2007) oxygen and elevated carbon dioxide atmospheres have been known to be effective to kill various insect pests for many years, but was generally applied at ambient or lower temperatures (Mitcham et al., 2003). Killing time is faster at elevated temperatures. Along with the forced hot-air, nitrogen is used to replace oxygen, and carbon dioxide is added. The mechanism of control is to increase the respiratory demand of the insects with the heat treatment while at the same time modifying the atmosphere, both of which contribute to death of the insect. Treatment times with high temperature CA can be one-half that with heat treatments alone.

Treatments with CA in combination with forced hot air have been tested for control of Mexican Fruit Fly and West Indian Fruit Fly in 'Manila' mangoes (Yahia and Ortega, 2000; Ortega and Yahia, 2000). 'Manila' mangoes tolerated treatment with 0% O_2 and 50% CO_2 at temperatures <44ºC and 50% RH for 160 min (Ortega and Yahia, 2000), but injury occurred at 44ºC and increased with increasing temperature. However, treatment at <44°C was not fully effective to control the two fruit fly pests (Yahia and Ortega, 2000).

High-temperature CA treatments were approved in 2008 by USDA APHIS for export of U.S. nectarines, sweet cherries and apples to control codling moth (*Cydia pomonella*), oriental fruit moth (*Grapholita molesta*) and western cherry fruit fly (*Rhagoletis indifferens)* (Neven & Rehfield-Ray 2006). However, these treatments are not yet approved for product imported into the U.S.. Details can be found in the USDA APHIS Treatment Manual
(http://www.aphis.usda.gov/import_export/plants/manuals/ports/downloads/treatment_pdf/05_07_t600schedules.pdf).

- Sweet Cherry: codling moth and western cherry fruit fly
    - 25 min at 116.6°F (47°C) with 1% O_2, 15% CO_2
    - 45 min at 113°F (45°C) with 1% O_2, 15% CO_2

- Apples: codling moth and oriental fruit moth
    - 12°C/h, 3h, chamber at 115°F (46°C) with 1% O_2, 15% CO_2
- Stone fruit: codling moth and oriental fruit moth
    - 12°C/h, 3h, chamber at 115°F (46°C) with 1% O_2, 15% CO_2
    - 24°C/h, 2.5h, chamber at 115°F (46°C) with 1% O_2, 15% CO_2

It is clear that high temperature CA treatments could be a successful option for fruit fly control in mango fruit, assuming the treatment will eventually be approved for fruit imported into the U.S. More research is needed on tolerance of each mango cultivar to optimize the temperature and atmosphere for effective fruit fly control. It is important to realize that the engineering design for this treatment must allow for a turnkey approach to treatment operation. There would be additional variables to monitor that could cause treatment failures, including the oxygen and carbon dioxide concentration as well as the temperature. It is not clear that the shorter treatment time or the improved fruit quality would be sufficient to warrant the extra expense of the equipment, but this treatment option appears worthy of further consideration. This is especially true since a large investment has not yet been made in forced-hot air treatment facilities. Insecticidal CA treatments could also be investigated at room temperature (68-77°F; 20-25ºC) as insects might be controlled within a period of 48 to 72 hours. If this approach can work, then a significant amount of energy (for heating and for cooling after the heating process) can be saved. Companies that build CATTS type systems include: Techni-Systems, Inc. (Chelan, WA; USA; www.techni-systems.com) and EcO2, Inc. (The Netherlands; www.eco2.nl/UK/index.htm).

Irradiation

Food irradiation is a process by which products are exposed to ionizing radiation to sterilize or kill insects and microbial pests by damaging their DNA. In 1986, the U.S. Food and Drug Administration (FDA) approved the use of radiation treatments of up to 1 kGy (100 krad) on fruits and vegetables. Radiation may be provided by gamma rays from cobalt-60 or cesium-137 sources, electrons generated from machine sources (e-beam), or by x-rays. Absorbed dose is measured as the quantity of radiation imparted per unit of mass of specified materials. The unit of absorbed dose is the gray (Gy) where 1 gray is equivalent to 1 joule per kilogram.

While much of the focus of irradiation use on fruits and vegetables in the past has been for extending shelf-life and reducing decay, it has been known for many decades that irradiation is effective at killing, sterilizing or preventing further development of a wide variety of insect pests of quarantine importance on perishable fruits and vegetables. Research has shown that the doses required for sterilization of most insects is below 0.75 kGy; while the dosages required for effective decay control are often greater than 1 kGy. Until relatively recently, the only irradiation treatment approved for quarantine use for the U.S. market was for the movement of papaya fruit from Hawaii to the mainland U.S. The protocol required the papayas be treated in Hawaii with 150 Grays of ionizing radiation for control of fruit fly pests. Unfortunately, this protocol, which was approved in 1989, was never used, in part because an irradiation facility was not approved to be built in Hawaii until nearly 10 years later. This highlights one of the potential challenges to irradiation treatment – building the facilities.

In May of 1996, the USDA APHIS published a policy statement in the Federal Register regarding their position concerning the use of irradiation as a treatment for quarantine pests in plants. Generic dosages were proposed and later accepted for various fruit fly species as shown in Table 3. The dosages were generic in the sense that the prescribed dose was deemed appropriate regardless of the commodity. Where more than one fruit fly species is present, the dose would be that for the most tolerant species. This generic approach was a departure from traditional quarantine treatment protocols approved by USDA which have been both insect species and commodity specific. Irradiation doses that are needed to kill the insect are higher than those tolerated by fruits, and therefore the other unique feature of irradiation treatments is that they are generally designed to sterilize insects, not to kill them. In the case of fruit flies, APHIS has established the criterion for a successful dose as the non-emergence of adults to prevent sterile adults from triggering control strategies if detected in traps within areas free of established fruit fly populations. Additional research may support changes to these minimum doses in the future (Torres-Rivera and Hallman, 2007).

USDA APHIS approved the use of irradiation to treat fruit for importation into the United States in 2002, but it was only in 2007 that India began shipping irradiated fruit to the U.S. Several countries are developing Work Plans with APHIS to initiate bilateral trade in products irradiated for phytosanitary purposes (Follett and Griffin, 2006). Irradiation has been used since 2004 to disinfest mangoes shipped from Australia to New Zealand of fruit flies without insurmountable incident (Torres-Rivera and Hallman, 2007).

Table 3. Generic irradiation doses for some fruit flies (Tephritid species)

Common Name	Scientific Name	Minimum Absorbed Dose (Gy)
Oriental fruit fly	*Bactrocera dorsalis*	250
Mediterranean fruit fly	*Ceratitis capitata*	225
Melon fly	*Bactrocera cucurbitae*	210
Caribbean fruit fly	*Anastrepha suspensa*	150
Mexican fruit fly	*Anastrepha ludens*	150
West Indian fruit fly	*Anastrepha oblique*	150
Sapote fruit fly	*Anastrepha serpentine*	150
Queensland fruit fly	*Bacterocera tryoni*	150
Non common name	*Bacterocera jarvisi*	150

According to APHIS, live stages of pests found in a commodity following a Plant Protection and Quarantine (PPQ) prescribed and approved irradiation treatment will be presumed by PPQ to have been effectively treated unless evidence exists to indicate that the integrity of the treatment was inadequate. This means that when irradiation is used as a quarantine treatment, there must be a good degree of trust between the trading partners.

Irradiation Facilities

Although gamma rays, high energy electrons, and x-rays all have similar effects, gamma rays are most commonly used in food irradiation because of their ability to deeply penetrate pallet loads of food. Gamma irradiation equipment irradiates packaged or bulk commodities by exposing the product to gamma energy from cobalt-60 in closed chambers, which range in size from single modular pallet irradiators to large contract irradiation facilities.

The actual cost of food irradiation is influenced by dose requirements, the food's tolerance of radiation, handling conditions (packaging and stacking requirements), construction costs, financing arrangements, and other variables particular to the situation (Forsythe and Evangelou, 1993). Irradiation is a capital-intensive technology requiring a substantial initial investment, ranging from $3 to $13 million. A major capital cost includes the radiation source (cobalt-60), hardware (irradiator, totes, conveyors, control systems), land (1 to 1.5 acres), radiation shields, and warehouse (preferably with cold storage). Operating costs include salaries (for fixed and variable labor, must be well trained), utilities, maintenance, taxes/insurance, cobalt-60 replenishment, etc. Radiation plants are costly and would be more economical if used essentially year-round. However, fresh fruit and vegetable production is seasonal. This would require facilities to be, at a minimum, shared among commodities with somewhat different harvest schedules.

System Integrity

Certain policies are required to ensure system integrity in the application of irradiation as a phytosanitary treatment. These policies focus on pretreatments, treatment and post-treatment conditions as well as required documentation and monitoring. Before treatment, packers and treatment facilities must maintain records concerning the sources of commodities; how untreated commodities are stored and handled in the irradiation facility and packaging requirements. During treatment, the absorbed dose must be measured and monitored, including dose mapping of the minimum and maximum dose utilizing calibrated dosimeters. After treatment, pests may continue to live and develop. Therefore, confidence in the adequacy of irradiation treatments rests with the assurance that the treatment is efficacious against the pest under specific conditions and has been properly conducted and the commodity safeguarded. This requires strict treatment procedures and well designed and closely monitored systems for treatment delivery and safeguards that assure system integrity. Following treatment, packages must be marked and labeled with treatment lot numbers to allow trace back if needed.

Consumer Considerations

Consumption of foods irradiated at doses up to 10 kG has been considered safe by the World Health Organization (WHO), Food and Agriculture Organization (FAO), and the International Atomic Energy Agency. While consumers have concerns associated with the safety of irradiation technology and its effects on food, research indicates that properly irradiated food does not pose a risk to consumers (Thorne 1983, OTA 1985). While studies have shown consumer acceptance of irradiated produce in the U.S. is increasing (Morrison, 1992), serious social and public policy issues remain. Some produce companies have shied away from irradiation because they fear a backlash from consumers, but attitudes appear to be shifting.

Dosimetry Considerations

The tolerance of mango fruit to irradiation treatment is generally good, but there are differences between varieties and stages of maturity (Table 4). The greater the dose that can be tolerated by the fruit, the less expensive the treatment process could be. If product is treated in a palletized form or in totes, which is feasible with cobalt-60 or cesium-137 irradiation sources, in order for the fruit in the center of the load to receive 150 Grays, the product on the outside may receive two to six times higher dosage (300 to 900 Grays). The higher dosage could cause damage to some mango fruit. The higher the dosimetry ratio (lowest to highest dose administered to a batch of fruit), the more flexibility the operator has, resulting in potentially lower costs to the shipper.

By disassembling the pallet and treating product in boxes, the range of doses received by the product would be much smaller, but the cost of treatment would be higher as compared to a pallet irradiator due to the additional labor involved, but would be similar to a tote irradiator since these boxes must also be de-palletized. E-beam's inability to penetrate more than approximately 3-inches (8-cm) means that treatment of mangoes in electron-beam facilities would need to be with individual boxes on a conveyor.

Mango Tolerance to Irradiation

Fruit damage by irradiation is a function of cultivar, irradiation dose and fruit maturity/ripeness at the time of treatment (Boag et al., 1990; Singh, 1990).
Symptoms of irradiation stress on fruits and fruit-vegetables include accelerated softening, uneven ripening, and surface damage. Irradiation stress is additive to other stresses (physical, chilling, water, etc.) which should be avoided to minimize the negative effects of ionizing radiation on fresh produce. Gamma irradiation has been tested in mango to control ripening, diseases and insects. Irradiation dosages that kill insects can sometimes damage the fruit. Table 4 presents a summary of mango cultivar response to irradiation treatment according to reports in the literature.

Mango fruit softening was not slowed by irradiation in the range of 0.1 to 1.2 kGy (Boag et al, 1990). Fruit which were partially ripe and in their climacteric were largely unaffected by irradiation: ¼ to ½ ripe Haden mangoes showed no change in the rate of ripening when treated at 250 Grays (Akamine and Goo, 1979).

Many researchers have explored potential effects of irradiation treatment on the composition of mango fruit, including sugars, acids, β-carotene, antioxidants and sensory quality. Gamma irradiated (600 and 900 Gy) Keitt mangoes were preferred for color, odor, taste and texture until after 9 days in storage (Lacroix et al., 1992). However, Hatton et al. (1961) reported impaired flavor of 'Irwin' and 'Sensation' mangoes after irradiation at doses of 100 to 150 Grays. Losses in Vitamin C in irradiated mango fruit were reported at doses higher than 750 Gy (Wenkam and Moy, 1968).

Table 4. Responses of some mango cultivars to irradiation treatment.

Cultivar	Dose	Response	Reference
Alphonso	0.5 – 2 kGy	Skin spotting and blackening	Dharkar et al. 1966
	250 Gy	10 day delay in ripening and no damage	Dharkar and Sreenivasan 1972
	> 250 Gy	Physiological damage, accelerated ripening	Sreenivasan et al., 1971
Haden			
Mature Green	≥ 250 Gy	Skin scalding	Akamine and Goo, 1979
¼ to ¾ ripe	Up to 750 Gy	No damage when treated after 5d at room temp.	Akamine and Goo, 1979
¼ ripe	≥ 750 Gy	Skin scald when treated after 6d at 55°F (12.8°C)	Akamine and Goo, 1979
½ ripe	1 kGy	Scalded when treated after 6d at 55°F (12.8°C)	Akamine and Goo, 1979
	> 1 kG	Pulp damage, failure to ripen, off flavor	Akamine and Goo, 1979
Irwin	100–150 Gy	Slightly impaired flavor	Hatton, 1961
Keitt	600-900 Gy	No extension of shelf life, preferred sensory	Lacroix et al., 1992
	≥ 500 Gy	Reduced decay; skin scalding	Spalding and Von Windeguth 1988
Kent -Colorbreak	1.5 to 3 kGy	softer	Ahmed and Dennison, 1971

Cultivar	Dose	Response	Reference
Kensington Pride			
Mature Green	≥ 300 Gy	Delayed ripening, lenticel damage, reduced ascorbic acid	McLauchlan et al., 1990
	750 Gy	Increased respiration, inhibited degreening	McLauchlan et al., 1990
Nahng Glahng Wahn	630 Gy	No textural effect, preferred In sensory test	Lacroix et al., 1992
	560–700 Gy	Controlled decay (anthracnose and SER), no effect on composition	Lacroix et al., 1991
Pirie	1 kGy	Skin bronzing, off flavor	Thomas, 1977
Sensation	100-150 Gy	Slightly impaired flavor	Hatton, 1961
Tommy Atkins	150 Gy	2 to 3 days delayed ripening	Spalding and von Windeguth, 1988
	≥ 500 Gy	Scald-like peel injury	Spalding and von Windeguth, 1988
	1 to 3.1 kG	Inhibited carotenoid synthesis and reduced ascorbic acid in storage	Reyes and Cisneros-Zevallos, 2007
	>1 kG	Flesh pitting and cell death, softening	Reyes and Cisneros-Zevallos, 2007; Moreno et al., 2006
	≥ 3.1 kGy	Unsatisfactory to sensory panelists	Reyes and Cisneros-Zevallos 2007

Decay Control

Anthracnose decay incidence was decreased with increasing radiation dose up to 600 Gy, in agreement with previous studies (Johnson et al., 1990). However, irradiation treatment up to 1 kGy does not provide complete control of anthracnose decay. Several researchers have found that a combination of hot water dip followed by irradiation treatment provided for good control of postharvest diseases. A dose of 750 Gy combined with a hot water dip at 104°F (40ºC) for 20 min or 122°F (50ºC) for 5 min was effective in controlling postharvest diseases in mangoes (Brodrick, 1979; Kohima and Buddenhagen, 1967). Spalding and Reeder (1986) reduced decay in mangoes with a combination of a 127.4°F (53ºC) dip in Imazilil followed by irradiation at 200 Gy.

Because utilizing a higher upper limit of dose results in easier logistics and lower cost to the grower, there is a danger that fruit might be exposed to higher doses than they can tolerate while still meeting the minimum phytosanitary dose. This could result in quality issues if practiced. It will depend on the tolerance of mango fruit cultivars to irradiation.

Commercial Irradiation Facilities for Fruit

Example in Hawaii. In Hawaii, an irradiation facility is available with an electron beam/x-ray source which has similar penetration to gamma sources. Product is stacked three boxes deep on a metal carrier and moved through the facility making two passes by the source. This keeps the max/min dose received down to 1.5 for most products. The facility has capacity to treat 30 million pounds per year if they run three shifts, but is currently only used at 1/3 to ½ capacity. According to Peter Follett at USDA ARS, the costs depend on the product being treated. For papaya and sweet potatoes, the charge is US$0.15 per pound and for rambutan, litchi and longan is US$0.50 per pound. Hawaii is considering building a gamma irradiation facility in the near future.

Example in Mexico. An older irradiation facility in Palo Alto still operates near Mexico City. Many tests were conducted at this facility in collaboration with USDA and FAO over a long period of time with several fruits, including mango and citrus, but this facility is not currently irradiating fruit for commercial purposes. A new facility has been established, the Sterigenics facility, in the state of Hidalgo, near Mexico City. Sterigenics Inc. expects to begin treating guava fruit in the near future, as soon as the government of Mexico approves the use of irradiation for quarantine treatment of fruit. They are also exploring the possibility of treating mango fruit. USDA APHIS visited the Sterigenics facility in Mexico in mid-September 2008 to certify the facility for treatment of guavas and mangoes. Sterigenics has collaborated with University scientists in Mexico to test the tolerance of guava fruit to irradiation doses up to 1 kGy and plan to do similar tests with mangoes. These tests will look at growing region, maturity and cultivar effects on tolerance to irradiation dose. They would like to know the upper limit of tolerance, because the higher this is, the more flexibility in how the product can be treated, determining what different products could be treated at the same time or with similar settings. Sterigenics is especially interested in the Manila mango which does not tolerate the hot water treatment well. They are considering building more facilities in Mexico if their preliminary work with fresh fruit is successful.

Sterigenics is a world-wide company that has irradiation facilities in many countries. Some of these facilities provide gamma irradiation and others provide electron beam irradiation. Their facility near Mexico City has been in operation for eight years and treats dried food products and medical supplies. The company officials indicate they can treat at a dosimetry ratio of 4 which would provide 600 grays at the upper end and 150 grays at the minimum; however they would prefer a ratio of approximately 6.5 allowing them to go up to 1 kG. Their facility has the capacity to treat approximately 25,000 pounds of fruit per hour when the entire product is treated at the same settings. The price to the grower or shipper depends on several factors: 1) dose required, 2) efficiency in loading the tote, and 3) volume of product treated. For the guava fruit, a tentative price of US$0.025/lb. has been estimated. This number may be higher for mango because the loading efficiency in the totes may be lower.

Figure 7. Product Handling through the Sterigenics Facility in Mexico City, Mexico

Fruit in boxes are loaded into totes

Pistons raise and lower the floor for easy loading

Product moving into treatment area

Cobalt 60 radiation source under water when product is not being treated

Position of totes when product is being exposed to radiation source

The fruit in this system are loaded into totes for movement past the radioactive source (Figure 7). The aluminum totes are 59 cm x 92 cm x 142 cm high. Each tote has a false floor that allows the product to be easily loaded into the top of the tote. The floor is lowered as more and more product is added. The false floor is stainless steel and is raised and lowered by pistons. Fourty-five totes are exposed to irradiation at one time and they rotate in a serpentine fashion through the maze so that each side of the tote is treated equally. The shortest cycle time through the irradiator is 1.5 minutes per position (1.5 x 45 positions = 90 minutes) for a total treatment time of 90 minutes minimum.

The Sterigenics facility in Mexico City does not currently have any cold storage or cooling capability. They currently schedule treatments for frozen or refrigerated products so that they are treated upon arrival and loaded back into a refrigerated vehicle quickly. They appeared open to the idea of including cold storage in a facility that would be treating a large amount of fresh fruit products.

Microwave or Radio Frequency Treatment

The microwave region of the electromagnetic spectrum is from 1 to 100 GHz, between infrared and FM radio, and is close to the radio frequency range. Radio frequency (RF) waves are at the lower frequency range of the electromagnetic spectrum, with longer wavelengths. Accepted frequencies for industrial purposes are 13.56, 27.12, and 40.68 MHz (Tang et al., 2000). RF energy generates internal heat by agitating molecules in the fruit with a very rapid change in charge within the electrical field. The advantages of RF heating are that it is very fast, can penetrate deep, and can sometimes heat insects more than fruit.

The time required to increase fruit center temperature to 116.6°F (47°C) in vapor heat treatments can be 45 minutes or longer, resulting in fruit susceptibility to heat damage (Varith et al., 2006). Rapid heating by microwave or radio frequency energy can reduce the potential for fruit damage. The concept of high-temperature-short-time treatment is possible to shorten the treatment time while retaining fruit fly control at the Probit 9 (quarantine security) level. The high-temperature-short-time concept is extensively used in food processing to minimize thermal degradation of food quality (Stumbo, 1973; Holdsworth 1997). Tang et al., (2000) proposed high-temperature-short-time thermal quarantine methods using radio frequency energy to control codling moth in in-shell walnuts at 122 to 129°F (50 to 54°C). Microwave heating was tested on mangoes for control of mango seed weevil in the late 1960's, but the researchers found that the fruit appeared "cooked" after treatment. More recently, Varith and Kiatsiriroat (2004) studied microwave heating on 'Chokanan' mango with a 2,450 MHz/8W microwave oven and found an increase of internal temperature up to 115°F (46°C) within 40 seconds. Heat distribution within the fruit depended on orientation, microwave power and treatment time. The horizontally positioned mango treated with 50% microwave power yielded better heat distribution than the vertical one.

A follow-up study by Varith and colleagues in 2006 compared a combination microwave followed by vapor heat treatment with the standard vapor heat treatment (heat with 131°F (55°C) air until center temperature reaches 116.6°F (47°C) and hold for 18 minutes) on Namdokmai Si Thong mangoes. Mango fruit were exposed to 50% power using a 2,450 MHz/800 Watt microwave oven. The mango was first placed horizontally within the oven and rotated while being heated with microwave power of 400 W for 40 seconds. Secondly, the mango was placed vertically and the radiation focused on the cheek, the thickest part of the fruit. The final process was a vapor heat treatment (saturated steam) at 131°F (55°C). After treatment, the fruit were hydrocooled with 80.6°F (25°C) water for 30 minutes in a shower. It took 2 min to raise the core temperature of the mango to 116.6°F (47°C) with microwave heating. When a hold time of 7 minutes in 131°F (55°C) vapor heated air was added, 100% mortality of oriental fruit fly eggs was achieved. Only 96% mortality was obtained with the vapor heat treatment at 113°F (55°C) air and an 18 minute hold when the fruit core reached 116.6°F (47°C). The combination treatment caused no skin browning while the vapor heat treatment did. Also, internal damage was much reduced with the combination treatment, with only slight internal tissue collapse at the apex of the pit. While these treatments have so far been accomplished on a very small scale utilizing single fruit treatments, the results indicate some promise for this treatment approach.

However, when multiple fresh fruit are treated in a batch, they must be immersed in a saline solution to prevent burning of the fruit at their contact points with other fruit due to concentration of electrical energy at the contact points. Small-scale studies with radio frequency heating of fresh fruit in a saline solution have shown some promise for sweet cherry (Monzon et al., 2006) and especially for persimmons (Monzon et al., 2007) and guavas.

Combinations of radio frequency heating with hot water immersion have also been explored for various fruits, including apples (Wang et al., 2006a), oranges (Birla et al., 2005) and sweet cherries (Monzon et al., 2006). Hot water assisted RF was tested for control of Mediterranean fruit fly in oranges, using heat exposures previously demonstrated to provide 100% mortality of Mediterranean fruit fly (Gazit et al., 2004). Fruit were pre-heated in 95°F (35°C) water (a non-damaging temperature) for 45 minutes prior to RF heating to 118.4°F (48°C) and holding the fruit at that temperature for 15 minutes. This treatment controlled Mediterranean fruit fly without affecting fruit quality (Birla et al., 2005). A similar treatment was better tolerated by sweet cherries than a hot water treatment alone. However, a similar approach with apple fruit resulted in excessive fruit damage

The practical implications for implementation of radio frequency or microwave treatments are difficult for fresh fruits in large scale systems due to the potential for large temperature variations in the treated load. In addition, the requirement for treating fresh fruit in a saline solution requires unique engineering solutions that have not yet been developed. Mango fruit appear to have good tolerance to microwave or radio frequency heating. However, it is not yet known if improvements in fruit quality would be sufficient to warrant the extra expense and engineering required for this treatment approach as compared with hot water or hot air, but it seems doubtful.

Systems Approach

The appropriate level of protection for an importing country can be achieved by the application of a single phytosanitary measure, such as inspection or a quarantine treatment, or a combination of measures. System approaches integrate biological, physical and operational factors to meet quarantine requirements. The combination of specific phytosanitary measures that provides overlapping or redundant safeguards is distinctly different from the use of a single risk mitigative technique. Such combinations vary in complexity; however, all require the integration of two or more measures that act independently of each other, the cumulative effect achieving the desired level of phytosanitary protection (i.e., a systems approach).

Specific mitigations may be selected from a range of pre-harvest and post-harvest options, and may include other safeguarding measures. Measures may be added or the strength of measures increased to compensate for uncertainty. At a minimum, for a measure to be considered for use in a systems approach, it must be: 1) clearly defined; 2) efficacious; 3) officially required (mandated); and 4) subject to monitoring and control by the responsible national plant protection organization. Systems approaches to risk mitigation have been specified in recent work plans for the importation of commodities, such as citrus from Chile and avocado from Mexico. A systems approach to mitigating risks involved with mango imports from Central or South America might combine a variety of measures, including ***some*** of the following:

1) certification of pest free areas, pest free places of production, or areas of low pest prevalence for certain quarantine pests, such as fruit flies;
2) programs (e.g., mechanical, chemical, cultural) to control pests within orchards;
3) preclearance oversight by USDA-APHIS officials;
4) packinghouse procedures (e.g., washing, brushing, inspection of fruit) to eliminate external pests;
5) quarantine treatments to disinfest fruit of internal and external pests;

6) consignments inspected and certified by importing country phytosanitary officials and APHIS, PPQ to be free of quarantine pests;
7) fruit traceable to state of origin, packing facility, grower, and orchard;
8) consignments subject to sampling and inspection after arrival in the United States; and
9) limits on distribution and transit within the United States.

Pest-free areas

As a sole mitigative measure, the establishment of pest-free areas or pest-free places of production may be completely effective in satisfying an importing country's appropriate level of phytosanitary protection. This option has proven to be successful in practice, obviating the need for post-harvest commodity treatments to achieve probit-9-level security. Establishment and maintenance of pest-free areas or production sites should be in compliance with international standards, but the specifics are usually negotiated between the exporting and importing countries.

Examples of some of the strategies employed in development and maintenance of pest free zones or areas of low pest prevalence are desribed below. Trapping is used to survey the area of pest populations. In surveys for fruit flies, such as *Anastrepha* spp., for which parapheromones are not available, minimal trap density in zones of high risk (areas having high probability of fly establishment or introduction) should be five traps per km^2 traps (e.g., McPhail) and these should be baited with protein hydrolysate. Trapping for other potential pests of concern may also be required in the absence of any postharvest treatment.

Areas of low pest prevalence

An area of low pest prevalence may comprise all of a country, part of a country, or all or parts of several countries, in which a particular pest species occurs at low population densities and which is or are subject to effective surveillance and control or eradication measures. Procedures for the establishment and maintenance of areas of low pest prevalence should comply with international standards. For example, elements of an operational plan for establishment and maintenance of such areas might include a geographic description to delimit the area; specification of an upper limit to pest densities; means to document and verify all necessary procedures and maintain records; specification of phytosanitary procedures (e.g., survey, pest control); and movement controls to prevent pest entry or re-entry into the area. The international standards recommend that the exporting country consult with the importing country in the early stages of implementation to ensure that importing country requirements are met. In particular, target or threshold population densities defining an area of low pest prevalence should be established in consultation with the importing country. Any protocol for establishing and maintaining a pest-free area or area of low pest prevalence also should include a pest-reporting procedure and emergency action plan to address target pest detections in the pest-free or low-prevalence zones.

Control program

Cultural, chemical, or mechanical means (e.g., orchard sanitation, pruning of dead and diseased branches, pre-harvest application of pesticides, fruit bagging) may be used to eliminate pests from orchards or prevent fruit infestation. Sanitation and pesticide applications, as essential components of best management practices, are mainstays of commercial fruit production. For fruit flies, in particular, sterile insect release and other controls may be employed as prophylactic measures or in response to pest detection, following guidelines in USDA. Simple physical barriers, such as paper or plastic bags, may be highly effective in protecting fruit from pests. For example, fruit bagging combined with protein bait sprays reduced fruit fly (*Bactrocera* and *Dacus* spp.) infestations in unspecified fruit by up to 98 percent (Sar et al., 2001). In pineapple guava, *Feijoa sellowiana*, effective control of *Anastrepha fraterculus* was achieved if bagging was commenced when fruit reached an average diameter of 22 mm (Hickel & Ducroquet, 1994).

Phytosanitary certification inspections and monitoring

Fruit should be sampled and inspected periodically during the growing season and after harvest. Orchards should be surveyed as much as twice per year, during which time 10 percent of the area of each orchard is inspected. At these times, a random sample of fruit (some from the ground), in a specified number of trees (at orchard edges) per ha, should be taken, inspected, and cut to detect a 0.00003 infestation rate (three infested fruit per 100,000).

Results of surveys must be negative for larvae of fruit flies. Production areas also may be subject to periodic, unannounced inspections by certified officials to ensure that they meet stipulated requirements for the issuance of a phytosanitary certificate that would be required for each consignment. Statistical procedures are available to verify, to a specified confidence level, the pest-free status of an area, given negative survey or trapping results.

Postharvest safeguards and packinghouse procedures

Containers of harvested fruit should be covered with tarpaulins or other covers and moved to the packinghouse in a fruit fly-proof conveyance in a timely manner (e.g., within three hours of harvest). Upon arrival at the packinghouse, a random sample of fruit per lot should be taken to be inspected for external pests and cut to reveal internal pests, each sample to be of sufficient size to detect a 0.00003 infestation rate. In the packinghouse, fruit should undergo mechanical brushing or other treatment to remove external pests. Fruit then should be immersed in a water bath containing surfactant and, perhaps, a surface sterilant, such as chlorine bleach (e.g., NaOCl). Surfactants, such as common dishwashing detergent, may show a high degree of insecticidal activity with minimal risk of phytotoxicity. All fruit should be inspected prior to packing. Consignments should be transported in sealed, refrigerated vehicles.

First Fruit Fly Free Zone in Texas

The first pest free area was established in the Rio Grande Valley of Texas for Mexican fruit fly in 1981. The program was developed and implemented over several years and after considerable research to demonstrate the validity and reliability of the trap survey as a means to monitor for fruit flies, to validate the type of trap used by cutting 10 to 20 thousand fruit over a two year period in the areas with traps, to evaluate sterile Mexican fruit fly releases for population suppression (75% suppression on native populations), and evaluate Malathion bait sprays for control of Mexican fruit fly. The rationale for initiating this fly free zone program was based on scientific and historical data showing low numbers of Mexican fruit flies in the production areas in July through April and low availability of fruit fly hosts during June through August. In addition, the Northern limit of distribution was thought to be limited at the Rio Grande Valley. Regardless, it took several years and a lot of research to quiet concern expressed by other citrus producing states in the U.S. regarding implementation of this fly free zone.

Mexican Campaign to Control Fruit Flies

In Mexico, a campaign against fruit flies was initiated in 1992 under a national plan. The initial plan had a 12-year time frame, but is still a work in progress. This plan considered the suppression, containment or eradication from Mexico of the four most economically and quarantine important fruit fly species (i.e., Mexican Fruit Fly, West Indian Fruit Fly, Sapote Fruit Fly, and Guava Fruit Fly), in order to develop free or low prevalence areas of these pests (Montoya et al. 2007). To reach this goal, the country was divided into three working regions, which were defined by their agroecological characteristics, the number of fruit fly species present in each region, and the size of the fruit-growing areas. In addition, a mass rearing facility was built to produce 300 million sterile *Anastrepha* spp. flies and 50 million parasitoids per week (Reyes et al. 2000). The technical plan was based on the integration of different technologies and strategies that have been applied using an area-wide approach. These were: (1) the use of specific lures and baits to detect and monitor fruit fly populations, (2) the use of cultural practices as mechanical control to destroy host fruits, (3) the application of selective toxic baits through aerial or ground applications, (4) the use of the sterile insect technique (SIT) against *A. ludens* and *A. obliqua*, (5) the establishment of quarantine procedures, and (6) the release of the fruit fly parasitoid *Diachasmimorpha longicaudata* (Ashmead) in specific regions and periods.

Table 5. Comparison of through-put and cost of alternative treatments.

Treatment Alternative	Through-put/Capacity	Cost	Source
Vapor Heat Treatment, Forced Hot-air	2.4 and 4.7 metric tons units per 4 hour maximum treatment time	EHK230MC (2.4 metric tons) $560,000* EHK460MC (4.7 metric tons) $1.1 million* *capital costs, installation extra	Sanshu Sangyo Co., Ltd.
Forced hot air chambers in Mexico	7 metric ton per treatment load	< $138,000 (capital cost of equipment)	Jose Sostenes Hernandez Gimeenez, Celaya, Gto
High Temperature Controlled Atmosphere	2,000 lbs. in bins per 3 hour treatment maximum time (1 bin system)	$48,000 (capital cost of equipment)	Techni-Systems, Chelan, WA
	2 pallet system (2,000 lbs.) per 3 hour maximum treatment time	$50,000 to $80,000 (capital cost of equipment)	Techni-Systems, Chelan, WA
	1,500 to 11,000 metric tons per year	$2.50 to 16.50 per metric tons	EcO2, The Netherlands
Irradiation	10,275 pounds per hour	$0.15 to $0.50 per lb. depending on fruit, dose and dosimetry (dose range allowed) (Capital cost approx. $4 million)	Electron beam/x-ray facility in Hawaii
	25,700 lbs. per hour at max. capacity (depends on dose range selected)	>$0.03 per lb. (Capital cost of facility approx. $10 to 12 million)	Sterigenics Cobalt 60 facility in Mexico City

(1 metric ton = 2,205 lbs.)

Table 6. Advantages and disadvantages of treatment options for disinfestation of mango fruit.

Treatment Method	Advantages	Disadvantages
Hot Water	-Facilities available -Less capital cost for new facilities -Many years of experience, system optimized -Provides decay control -Relatively simple to operate	-Narrow tolerance to prevent injury -Need to cool the fruit after treatment -potential food safety risk from immersion of hot fruit in cool water
Forced Hot Air	-Reduced potential for fruit injury -Some decay control	-Few good facilities currently available -Longer treatment than hot water -More complex to operate -Need to cool the fruit after treatment -potential food safety risk from immersion of hot fruit in cool water
High Temperature CA	-Less potential for fruit damage than forced-hot air alone -Shorter treatment time than forced hot air -Some decay control	-Additional research needed to prove efficacy against fruit fly pests over hot air alone and confirm fruit tolerance -More complex to operate -Facilities would need to be built -More parameters to measure and that may be out of range leading to treatment failure Longer treatment than hot water Need to cool the fruit after treatment -potential food safety risk from immersion of hot fruit in cool water

Treatment Method	Advantages	Disadvantages
Irradiation	-Relatively short treatment time -Fruit are not heated during treatment; no extra cooling required -No added food safety risk	-Limited number of facilities -Potential for fruit damage, especially at higher doses -Chance for consumer resistance
Radiofrequency/microwave	-Rapid treatment, could be accomplished on the packing line	- Equipment not yet commercialized for fresh fruit Likely will be complex to operate -Fruit will need to be cooled -potential food safety risk from immersion of hot fruit in cool water
Systems Approach, Fly Free Zone	-No physical treatment that could damage fruit or delay their marketing	-Expensive to achieve and maintain - Constant risk of loosing security and therefore market -May not be achievable

Future Research Needs

In addition to the recommended improvements to the hot water treatment protocol and improvements in temperature management, the National Mango Board should consider supporting the following activities in the future.

1. *Tolerance of mango cultivars to irradiation treatment*
   The maximum number of grays that can be tolerated by each mango cultivar needs to be determined. Other factors that should be tested are various stages of maturity for each cultivar, beginning with immature fruit to partially ripe. In addition, the influence of fruit temperature before and during irradiation treatment on fruit tolerance should be tested.

2. *Forced hot-air and high temperature controlled atmosphere treatment engineering*
   Contract an engineer to evaluation existing forced hot-air systems and, if needed, design an improved system for mango fruit. The system should be designed to achieve the most uniform fruit temperatures during heating and control of humidity to control water loss. The system could be designed with

and without controlled atmosphere capabilities to allow for high temperature CA treatments.

3. *High temperature controlled atmosphere treatment efficacy*
   Additional research is needed to determine the efficacy of forced hot-air treatments with controlled atmospheres against fruit fly pests of significance in mango fruit of various types. This efficacy should be determined before engineering work is contracted.

Conclusions

There are several potential alternatives to the hot water protocol for disinfestation of fruit fly species from mango fruit. Some of these alternatives are readily available and approved treatments (forced-hot air), and others will soon be available to a limited extent (irradiation). Other treatment options will require more time and perhaps additional research for development (high temperature controlled atmosphere, systems approach, radio frequency). None of the alternatives could be used without risk to fruit damage, although forced-hot air (with or without CA) and irradiation have potential to be less damaging, and shifting to alternative treatment options could be very capital intensive. Our investigations indicate great potential for improving fruit handling before and after the hot water treatment to mitigate the potential damaging effects of this treatment. Implementation of hydrocooling practices for all hot water treated fruit could greatly improve fruit quality. Good fruit temperature management is important regardless of the quarantine treatment utilized.

References

Ahmed, E.M. and R.A. Dennison. 1971.Texture profile of irradiated mangoes and peaches. Journal of Texture Studies 2:489-496.

Akamine, E.K. and T. Goo. 1979. Effects of ionizing energy on Haden mangoes. Hawaii Agricultureal Experiment Station Research Report 205: 1.

Armstrong, J.W. and R.L. Mangan. 2007. Commercial quarantine heat treatments. In: Tang et al, eds., Heat Treatments for Postharvest Pest Control, CABI, Oxon, UK.

Armstrong, J.W., J.D. Hansen, B.K.S. Hu, and S.A. Brown. 1989. High-temperature forced-air quarantine treatment for papayas infested with tephritid fruit flies (Dipterna: Tephritidae) Journal of Economic Entomology 82:1667-1674.

Birla, S.L., S. Wang, J. Tang, J. Fellman, D. Mattinson, and S. Lurie. 2005. Quality of oranges as affected by potential radio frequency heat treatments against Mediterranean fruit flies. Postharvest Biology and Technology 38:66-79.

Boag, T.S., G.I. Johnson, M.E. Izard, C. Murray, and K.C. Fitsimmon. 1990. Physiological responses of manoges cv. Kensington Pride to gamma irradiation treatment as affected by fruit maturity and ripeness. Annals of Applied Biology 116:177-187.

Brodrick, H.T. 1979. The influence of radiation on plant micro-organisms with reference to fruit and vegetables. Proc. National Symposium of Food Irradiation, South African Atomic Energy Board, Pretoria.

De Leon, P., C. Munoz, L. Perez, F. Diaz de Leon, C. Kerbel, L, Perez Flores, S. Esparza, E. Bosquez, and M. Trinidad. 1997. Hot-water quarantine treatment and water-cooling of Haden mangoes. Acta Horticulturae 445.

Dharkar, S.D. and A. Sreenivasan. 1972. Irradiation as a method for improved storage and transportation of mangoes. Acta Hort. 24:259.

Dharkar, S.D., K.A. Savagaon, A.N. Srirangarajan, and A. Sreenivassan. 1966. Irradiation of mangoes. II. Radiation effects on skin-coated ‘Alphonso’ mangoes. J. Food Science 31:870.

Esquerra, E.B. and M.C.C. Lizada. 1990. The Postharvest behaviour and quality of 'Carabao' mangoes subjected to vapour heat treatment. ASEAN Food Journal 5:6-12.

Ezquerra, E.B., S.R. Bresna, M.U. Reyes, and M.C.C. Lizada. 1990. Physiological breakdown in vapour heat treated 'Carabao' mango. Acta Hort. 269:425-434.

Forsythe and Evangelou. 1993. Costs and benefits of irradiation and other selected quarantine treatments for fruit and vegetable imports to the United States of America. Issue Paper. Proceedings of an International Symposium on Cost-Benefit Aspects of Food Irradiation Processing.

Follett, P.A., M. Yang, K.H. Lu, and T.W. Chen. 2007. Irradiation for Postharvest control of quarantine insects. Formosan Entomol. 27:1-15.

Follett, P. and R.L. Griffin. 2006. Irradiation as a phytosanitary treatment for fresh horticultural commodities: Research and regulations. In: Food Irradiation Research and Technology, Sommers, C.H. Sommers, and X. Fan, Eds., Blackwell Publishing, 2006. 317 pp.

Gazit, Y., Y. Rossler, S. Wang, J. Tang and S. Lurie. 2004. Thermal death kinetics of egg and third instar Mediterranean fruit fly *Ceratitis capitata* (Wiedemann) (Diptera: Tephritidae). Journal of Economic Entomology 97:1540-1546.

Hallman, G.J. and Armstrong, J.W. (1994) Heated air treatments. In: Sharp, J.L. and Hallman, G.J. (eds*.). Quarantine Treatments for Pests of Food Plants.* Westview Press, Boulder, CO, pp. 149-163.

Hansen, J.D. and J.A. Johnson. 2007. Introduction. In: Tang, J., E. Mitcham, S. Wang and S. Lurie, Eds., Heat Treatments for Postharvest Pest Control: Theory and Practice, CAB International, Wallingford, Cambridge.

Hatton, T.T., L. Berahan, and W.R. Wright. 1961. Preliminary trials of radiation on mature green 'Irwin' and 'Sensation' mangoes. Proc. 21st Annual Meeting Florida Mango Forum, 15.

Hickel, E.R. and J.P. Ducroquet. 1994. Ocorrência de mosca das frutas *Anastrepha fraterculus* em frutas golabeira serrana. Anais da Sociedade Entomológica do Brasil.

Holdsworth, S.D. 1997. Thermal processing of packaged foods. Blackie Academic and Professional, London, UK.

International Atomic Energy Agency, The Food and Agricultural Organization of the United Nations, and the World Health Organization. Aix-En-Provence, Vienna. March 1-5, 1993.

Jacobi, K.K and L.S. Wong. 1990. Quality of ‘Kensington’ mango (*Mangifera indica* Linn.) following hot water and vapour-heat treatments. Postharvest Biology and Technology 1:349-359.

Jacobi, K., J. Giles, E. MacRae, T. Wegrzyn. 1995. Conditioning ‘Kensington’ mango with hot air alleviates hot water disinfestation injuries. HortScience 30: 562-565.

Jacobi, K.K., MacRae, E.A., Hetherington, S.E. (2001). Postharvest heat disinfestation treatments of mango fruit. *Scientia Horticulturae*. 89. 171-193.

Johnson, G.I., T.S. Boag, A.W. Cooke, M. Izard, M. Panitz, and S. Sangchote. 1990. Interaction of post harvest disease control treatments and gamma irradiation of mangoes. Ann. Applied Biology 116:245-257.

Kojima, E.S. and I.W. Buddenhagen. 1967. Studies on gamma irradiation in relation to Postharvest diseases of papayas and mango. Rep. 1966-1967, UH235-p5-3, p. 54. U.S. Atomic Energy Commission, Washington, D.C.

Lacroix, M., L. Bernard, M. Joblin, S. Milot, and M. Gagnon. 1992. Effect of irradiation on the biochemical and organoleptical changes during the ripening of papaya and mango fruits. Rad. Phys. Chem. 35:296-300.

Laidlaw, W. G., J.W. Armstrong, H.T. Chan, and E.B. Jang. 1996. The effect of temperature profile in heat-treatment disinfestation on mortality of pests and fruit quality. Proceedings of the International Conference on Tropical Fruits: Global Commercialization of Tropical Fruits, Kuala Lumpur, Malaysia, pp. 343-352.

McLauchlan, R.L., Mitchell, G.E., Johnson, G.I. and Wills, P.A. 1990. Irradiation of Kensington mangoes. Acta Horticulturae 269:469-476.

Mitcham, E.J., T. A. Martin, S. Zhou and A.A. Kader. 2003. Summary of CA for arthropod control on fresh horticultural perishables. Acta Horticulturae

Monzon, M.E., B. Biasi and E.J. Mitcham. 2007. Effect of radio frequency heating on the quality of ‘Fuyu’ persimmon fruit as a treatment for control of the Mexican fruit fly. HortScience 41:1-5

Monzon, M.E., W. V. Biasi, T.L. Simpson, J. Johnson, X. Feng, D.C. Slaughter, and E.J. Mitcham. 2006. Effect of radio frequency heating as a potential quarantine treatment on the quality of ‘Bing’ sweet cherry fruit and mortality of codling moth larvae. Postharvest Biol. Technol. 40:197-203.

Montoya, P., J. Cancino, M. Zenil, G. Santiago and J. M. Gutierrez. 2007. The Augmentative Biological Control Component in the Mexican National Campaign Against *Anastrepha* spp. Fruit Flies. In: Area-Wide Control of Insect Pests From Research to Field Implementation, M. J. B. Vreysen, A. S. Robinson and J. Hendrichs, eds., Springer, Netherlands.

Moreno, M., M.E. Castell-Perez, C. Gomes, P. F. Da Silva, and R.G. Moreira. 2006. Effects of electron beam irradiation on physical, textural, and microstructural properties of ‘Tommy Atkins’ mangoes (*Mangifera indica* L.). J. Food Sci. 71:80-86.

Morrison. 1992. Food irradiation still faces hurtles. Food Review. October-December, pp. 11-15

Neven, L.G. and E.J. Mitcham. 1996. CATTS (Controlled Atmosphere Temperature Treatment System): A novel tool for the development of quarantine treatments. Amer. Entomol. 42:56-59.

Neven, L.G. and L. Rehfield-Ray. 2006. Combined heat and controlled atmosphere quarantine treatments for control of Western cherry fruit fly. J. Econ. Entomol. 99(3):658-663.

OTA. 1985. Food Irradiation: New perspectives ona controversial technology. Rosanna Mentzer Morrison and Tanya Roberts, Office of Technology Assessment, Congress of the United States, Washington, DC, December 1985.

Ortega-Zaleta, D. and Elhadi M. Yahia. 2000. Mortality of eggs and larvae of *Anastrepha obliqua* (MACQUART) and *A. ludens* (LOWE) (Diptera: Tephritidae) with controlled atmospheres at high temperature in mango (Mangifera indica) cv Manila. Folia Entomologica Mexicana (In Spanish) 109:43-53.

Paull, R.E., Armstrong, J.W. (1994). Introduction. In: Paull, R.E., Armstrong, J.W. (Eds.), Insect Pests and Fresh Horticultural Products: Treatment and Responses. CAB International International, Wallingford, UK, pp.1-33.

Reyes, L.F. and L. Cisneroa-Zevallos. 2007. Electron beam ionizing radiation stress effects on mango fruit (Mangifera indica L.) antioxidant constituents before and during postharvest storage. J. Agric. Food Chem. 55:6132-6139.

Reyes, J.F., G.M. Santiago, and M. Hernßndez. 2000. The Mexican Fruit Fly Eradication Programme, pp 377-380. *In* Tan, K. H. (ed.), Proceedings: Area-Wide Control of Fruit Flies and Other Insect Pests. International Conference on Area-Wide Control of Insect Pests, and the 5th International Symposium on Fruit Flies of Economic Importance, 28 May-5 June 1998, Penang, Malaysia. Penerbit Universiti Sains Malaysia, Pulau

Sharp, J.L., M.T. Ouye, S.J. Ingle, and W.G. Hart. 1989a. Hot-water quarantine treatment for mangoes from Mexico infested with Mexican fruit fly and West Indian fruit fly (Diptera: Tephritidae). J. Econ. Entomol. 82:1657-1662.

Sharp, J.L., M.T. Ouye, S.J. Ingle, W.G. Hart, W. R. Enkerlin et al. 1989b. Hot-water quarantine treatment for mangoes from the State of Chiapas, Mexico, infested with Mediterranean fruit fly and *Anastrepha serpertina* (Wiedemann) (Diptera: Tephritidae).

Shellie, K.C. and R. L. Mangan, 2000. Postharvest disinfestation treatments: response of fruit and fruit fly larvae to different heating media. Postharvest Biology and Technology 7:151-160.

Shellie, K.C. and R.L. Mangan. 2002. Cooling method and fruit weight: Efficacy of hot water quarantine treatment for control of Mexican fruit fly in mango. HortScience 37:910-913.

Shukla, R.P.; Tandon, P.L. (1985) Bio-ecology and management of the mango weevil, *Sternochetus mangiferae* (Fabricius) (Coleoptera: Curculionidae). *International Journal of Tropical Agriculture* **3**, 293-303. Sing. 1990.

Singh, H. 1990. Chemical aspects of irradiated mangoes: A review; Atomic Energy of Canada Ltd., 10186 Pinawa Manitoba RDE 1LO (Canada).Whiteshell Nuclear Research Establishments, June.

Spalding, D.H. and W.F. Reeder. 1986. Decay and acceptability of mangoes treated with combinations of hot water, imazalil and gamma radiation. Plant Disease 70:1149-1151.

Spalding, D.H. and D.L. von Windeguth. 1988. Quality and decay of irradiated mangoes. HortScience 23:187-189.

Spalding, D.H., J.R. King, and J.L. Sharp. 1988. Quality and decay of mangoes treated with hot water for quarantine control of fruit fly. Trop. Sci. 28:95-101.

Sreenivasan, A., P. Thomas, S.D. Dharkar, 1971. Physiological effects of gamma radiation on some tropical fruits. Disinfestation of Fruit by Irradiation, International Atomic Energy Agency, Vienna, pp. 65–91.

Stumbo, C.R. 1973. Thermobacteriology in Food Processing. Academic Press, Inc. New York.

Sivapalasingam, S., E. Barrett, A. Kimura, S. Van Duyne, W. De UIT, M. Ying et al., 2003. A multistate outbreak of *Salmonella enterica* Serotype Newport infection linked to mango consumption: Impact of water-dip disinfestation technology. Clinical Infectious Diseases 37:1585-1590.

Suslow, T. 2004. Oxidation-reduction potential (ORP) for water disinfection monitoring, control and documentation. University of California, Agricultural and Natural Resources Publication #8149, http://postharvest.ucdavis.edu

Tang, J., J.N. Ikediala, S. Wang, J.D. Hansen, and R.P. Cavalieri. 2000. High-temperature-short-time thermal quarantine methods. Postharvest Biol. Technol. 21:129-145.

Thomas, A.C. 1977. Radiation preservation of sub-tropical fruits. Food Irradiation Newsletter. Joint FAO/IAEA Div. of Atomic Energy in Food & Agriculture. Int'l Atomic Energy Agency, Vienna. 1(2): 19.

Thomas, P. and M.T. Janave. 1975. Effect of gamma irradiation and storage temperature on carotenoids and ascorbic acid of mangos ripening. J. Sci. Food. Agric. 26:1503-1512.

Thorne. 1983. Developments in Food Preservation. Applied Science Publishers Ltd., S. Thorne, ed., Essex, England. Chapter 2.

Torres-Rivera, Z. and G.J. Hallman. 2007. Low-dose irradiation phytosanitary treatment against Mediterranean fruit fly (Diptera:Tephritidae). Florida Entomologist 90(2):343-346.

Varith, J., W. Sirikajornjaru, and R. Kiatsiriroat. 2006. Quarantine treatment on mango using microwave-vapor combined process. Proceedings of the American Society of Agricultural and Biological Engineers Annual International Meeting, Portland, Oregon, 9–12, July, 2006.

Varith, J. and T. Kiatsiriroat. 2004. Effects of microwave power, treatment time and sample orientation on heat distribution in mango. ASAE Paper No. 04-6104. St. Joseph, Mich.: ASAE.

Wang, S., S.L. Birla, J. Tang and J.D. Hansen. 2006. Postharvest treatment to control codling moth in apples using water-assisted radio frequency heating. Postharvest Biology and Technology 40:89-96.

Wenkam, N.S. and A.P. Moy. 1968. Nutritional composition of irradiated fruit. 1. Mango and Papaya, Univ. Coll., Tropical Agr., AEC Rpt., VH-235-P-5-4, pp. 126-135.

WHO (World Health Organization). 1981. Wholesomeness of irradiated food: Technical Report Series No. 659. WHO Geneva.

WHO (World Health Organization). 1994. Agreement on the application of sanitary and phytosanitary measures. GATT Uruguay Round Agreements. World Trade Organization, Geneva.

Yahia, E.M. and J.P. Campos. 2000. The effect of hot water treatment used for insect control on the ripening and quality of mango fruit. Acta Horticulturae 509:495-501.

Yahia, E.M. and D. Ortega. 2000. Mortality of eggs and third instar larvae of *Anastrepha ludens* and *A. obliqua* with insecticidal controlled atmospheres at high temperatures. Postharvest Biology and Technology 20:295-302.