THERMAL DESIGN OF SHIPPING CONTAINERS FOR BENEFICIAL INSECTS

M. E. Casada, M. S. Ram, P. W. Flinn

ABSTRACT. *The use of chemical pesticides to control stored product insects can be reduced with Integrated Pest Management (IPM) practices such as the use of natural enemies, like parasitoids, to control harmful insects. In this study, improved specifications were developed for shipping containers to deliver healthy beneficial insects to IPM practitioners. Heat transfer through the container walls was evaluated to determine the amount of insulation and natural refrigerant (such as ice) necessary for maintaining the internal temperature in the desirable range throughout the shipping time and was based on recommended temperature limits for commercial shipments. An energy balance on the shipping containers was used to provide the needed design equation to specify the insulation level. Data were obtained from containers with temperature-monitoring sensors when shipped by overnight express from a cooperating supplier's laboratory to GMPRC. Also, standard frozen gels and other potential natural refrigerants were compared in laboratory tests of the containers at times and temperatures comparable to those measured in the experimental shipments. The 0.6% water in dioxane mixture had the best results of the solvents evaluated as refrigerants.*

Keywords. *Insects, Integrated Pest Management, IPM, Heat transfer, Natural refrigeration, Shipping, beneficial insects, Insect transport, Temperature monitoring.*

Beneficial insects, parasitoids, and predators can provide an effective means of controlling pest insects without the use of chemical pesticides. Beneficial insects are used frequently for integrated pest management (IPM) control of harmful insects in the field (Simmonds et al., 1976). Several studies have also found beneficial insects effective for control of stored grain insect pests (Arbogast, 1984; Schöller et al., 1997). In addition, pest populations have not been found to develop resistance to beneficial insects (Hokkanen et al., 1995). When these beneficial insects are produced in commercial facilities, large numbers of the insects are shipped to users, who may be located anywhere in the world. Insects require a low shipping temperature, usually near 10°C, so they will be inactive and stay healthy during transit.

Express shipping of these beneficial insects is used to limit the transit time, but a refrigeration source is still required to keep the containers cool during transport. Natural refrigeration can generally provide adequate cooling with minimal expense. Producers of beneficial insects have developed some creative packaging schemes but frequently don't have the technical expertise to analyze the heat transfer as needed to determine design criteria for the containers. Effective packaging continues to be a concern to many producers who have requested better containers and specifications to protect the beneficial insects during shipment.

Federal Express® recommends packaging that allows for a minimum of 30 h of transit time. Experience indicates express shipping normally takes less than 30 h, but that is not always certain. Table 1 shows the suggested extreme temperatures to prepare for when shipping perishable items by Federal Express®. The average exposure temperature will generally be more important for calculating refrigeration requirements. The best estimate for a given shipment can be hard to determine. An average exposure temperature of about 21°C (70°F) during a 15-h fall shipment by air (California to Kansas) was recorded in this study.

An insulated container with natural refrigeration offers a simple method of shipping at low temperatures. With proper design, these insulated containers can be effective for shipping beneficial insects at a constant shipping temperature, such as the frequently used 10°C. The physics of the natural refrigeration process with an insulated container can be evaluated as steady state heat transfer. The interior container temperatures can be predicted from an energy balance. When the ambient temperature is higher than the shipping temperature, heat gain by conduction through the walls of the box is offset by natural refrigeration (e.g., provided by melting refrigerant absorbing this heat, or a similar phase change process). The amount of heat absorbed by the phase change process will be determined by the heat of fusion, H_{sf}, of the natural refrigerant.

Ice, with a relatively high heat of fusion, has long been used effectively as a natural refrigerant. The liquid produced by the melting refrigerant, which would be detrimental in a cardboard container, the limited duration of cooling, and

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The authors are **Mark E. Casada, ASABE Member Engineer,** Lead Scientist, Agricultural Engineer, **M. S. Ram,** Chemist, and **Paul W. Flinn,** Research Biologist, USDA-ARS Grain Marketing and Production Research Center, Manhattan, Kansas. **Corresponding author:** Mark E. Casada, 1515 College Ave., Manhattan, KS 66502; phone: 785-776-2758; fax: 785-537-5550; e-mail: casada@ksu.edu.

Table 1. Maximum and minimum shipping temperature expectations.[a]

	Truck	Plane	Cargo	Extreme
Maximum	140°F	90°F	90°F	160°F
Minimum	-60°F	65°F	0°F	-80°F
Average	Seasonal	75°F	-	-

[a] Source: FedEx (1998).

sometimes the weight, are usually the main drawbacks. Frozen gels provide the benefits of ice without the moisture problems. For shipping insects, ice and the replacement gels have the drawback of maintaining a cooler than desired temperature. Biotactics, Inc. (Perris, Calif.) uses one of the more successful containers in the industry: a two-compartment container. The two-compartment container partially overcomes this cool temperature problem by maintaining a higher temperature for the insect samples than for the gel packs. When arranged correctly, this is effective for one constant shipping ambient temperature. In practice, however, ambient shipping temperatures vary widely both with season and during each overnight shipment — the greater variation in shipping temperatures, the greater the error that will be experienced with a two-compartment design. In addition, the arrangement of the gel packs in the two-compartment container is nearly an art that has not been applied effectively by most producers of beneficial insects other than the container originator.

A frozen solvent with a melting point at the desired shipping temperature, such as 10°C, should provide a relatively simple method to produce the desired temperature during shipping. If the products are surrounded by packs with a melting point near the desired temperature, they naturally maintain the product near the melting point temperature of those surrounding packs. The melting point of water, 0°C, is too low for use directly surrounding the products. The most common commercial gel pack products have melting points equal to water or lower than water, rather than a higher melting point, which is needed with insects. Presumably, this is due to a greater demand for products in that temperature range. The published melting points of other solvents (NIST, 2005) revealed several solvents that may be effective as natural refrigerants in this application because they have melting points closer to the temperatures required for shipping beneficial insects.

A shipping temperature of 10°C is appropriate for most beneficial insects and mites because they all are poikilothermic (cold blooded). At 10°C they are warm enough to remain healthy for extended periods — up to one or two months — and cool enough to stay inactive. It is important that they be inactive so their respiration rate remains low. Experience in our lab has shown that at temperatures below 15°C the heat of respiration from beneficial insects is negligible. If the insects warm enough that heat of respiration becomes significant, they could produce a vicious cycle of increasing activity and increasing temperature that would result in significant mortality. Beneficial insect mortality has been minimized in our lab below 15°C and above 5°C. Because of inevitable temperature variations in transit, it is desirable to target 10°C during shipping so small swings of temperature do not yield temperatures outside of the acceptable range of 5°C to 15°C.

Objectives

The overall goal of this work was to develop improved specifications and methods for shipping containers to deliver healthy beneficial insects for Integrated Pest Management (IPM) practitioners. Specific objectives were to: (1) determine temperatures inside existing shipping containers for beneficial insects during overnight shipment, (2) evaluate alternatives to using water as the natural refrigerant in the containers, and (3) calculate specific tradeoffs required between insulation thickness and mass of natural refrigerant required in the containers.

Analysis of Heat Transfer

Figure 1 shows a steady state energy balance for a container with a natural refrigerant. With no refrigerant in the container, there is no heat generation from melting refrigerant and the heat gain through walls would cause a temperature rise in the container, as long as it is warmer outside than inside. (The heat generation term would be a heat loss if a natural refrigerant were present.) When a natural refrigerant is present, it maintains an approximately constant temperature near its melting point inside the container.

This energy balance (fig. 1) yields the following equation:

$$\bar{q}_{ref} - \bar{q}_{loss} = \frac{C \cdot \Delta T_{rise}}{t} \tag{1a}$$

or

$$H_{sf} \cdot M - \frac{A_{eff}}{R_T} \cdot t \cdot \Delta T_{wall} = C \cdot \Delta T_{rise} \tag{1b}$$

where

$\bar{q}_{ref}$ = heat generation by refrigerant (W)
$\bar{q}_{loss}$ = heat loss through walls (W)
c_p = average specific heat capacity of material (J/kg°C)
C = $c_p M_t$ = average heat capacity of material (J/°C)
ΔT_{rise} = average temperature rise of material (°C)
ΔT_{wall} = $T_{exp} - T_{in}$ = temperature difference across walls (°C)
T_{exp} = exposure (ambient) temperature (°C)
T_{in} = refrigerated temperature inside shipping container (°C)
t = process time (s)

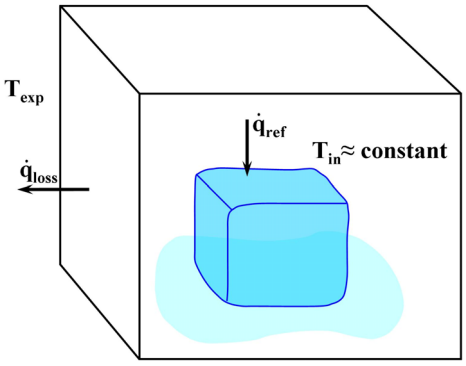


Figure 1. Steady state energy balance.

H_{sf} = latent heat of fusion of refrigerant (J/kg)
M = total mass of natural refrigerant (kg)
M_t = total mass of all material inside container (kg)
A_{eff} = effective area of container for heat gain (m^2)
R_T = total resistance of walls (m^2 °C/W)

As long as the refrigerant remains effective, the temperature inside the container does not increase and the time before the natural refrigerant melts can be determined from the ratio of the heat content of the refrigerant to the heat gain through the walls. Alternately, the same equations can be used to calculate the mass of refrigerant required to maintain the refrigeration effect for a specified time. When the temperature is constant in the container, equation 1 becomes:

$$M = \frac{A_{eff}}{H_{sf} \cdot R_T} t \cdot \Delta T_{wall} \quad (2)$$

Calculations of heat gain through the walls should be accurate as long as the following inherent assumptions hold: 1) heat transfer is steady state, 2) all geometry and material properties are known, and 3) the natural refrigerant is uniformly distributed inside the container.

The third assumption could be a problem depending on the location of refrigerant in the container. The degree of deviation from constant temperature depends on the exact arrangement inside the container, combined with the variation in outside temperature. With the refrigerant separated from the sample in a two-compartment arrangement with the refrigerant compartment at one temperature and the sample compartment at another temperature, the deviation could be significant when the outside temperature varies. With refrigerant completely surrounding the sample, temperature deviation should be minimized. Surrounding the sample with refrigerant is an obvious and recommended arrangement for the container (FedEx, 1998). With no variation in outside temperature, once the interior temperatures reach steady-state, there should be no variation over time inside the container regardless of the arrangement.

PROCEDURES

NATURAL REFRIGERANT ALTERNATIVES

There are other solvents, and solvent mixtures, with melting points closer to the preferred shipping temperatures for many beneficial insects. Table 2 lists several with promising characteristics in the temperature range of interest. Water is listed as a standard of comparison, although water gel packs have a melting point lower than the temperature range desired for beneficial insects. The other compounds have various drawbacks in comparison to the water gel packs. The major observed drawbacks are:

- They have lower heats of fusion, requiring a larger mass for the same refrigeration effect.
- While these examples were selected in part because they are not excessively hazardous, they are not as safe as water.
- Some have freezing problems, e.g., glycerol, hasn't worked well because it tends to super cool instead of freezing.

LABORATORY TESTS

Container shipments were simulated in lab tests at the USDA-ARS/GMPRC with the compounds listed in table 2 as the natural refrigeration source. All of the solvents and mixtures were evaluated first by placing them in a freezer and monitoring basic freezing characteristics. In the first set of laboratory container tests, small containers of frozen benzene, glycerol, and a standard frozen gel (water equivalent) were prepared and tested in identical insulated shipping containers when exposed to room temperature (ca. 22°C). The containers were sealed linear low density polyethylene (LLDPE) bags (10 × 15 cm; 0.114 mm thickness) containing a total of ca. 200 g for each material. Multiple small compartments were used to contain the

Table 2. Evaluation of properties of natural refrigerant alternatives.

	Melting Point		Heat of Fusion, H_{sf}		Liquid Density[b]	
Compound	°C	(°F)	kJ/kg[a]	(cal/g)	g/mL	Comments
Water	0	(32)	334	(79.8)	1.03	Standard
Benzene	5.6	(42)	127	(30.3)	0.87	Safety issues
Glycerol	18.0	(65)	199	(47.4)	1.26	Super cools
p-Xylene	12.5	(54)	161	(38.5)	0.86	Useful in mixture with lower melting point
t-Butanol	25.8	(78)	91.5	(21.9)	0.80	High cryoscopic constant 8.4 deg/m (ice is 1.8 deg/m)
85% t-Butanol-15% glycerol mix	12.1	(54)	108	(25.7)	0.87	Low heat of fusion
Hexadecane	17.8	(64)	227	(54.3)	0.773	Useful in mixture with lower melting point
Tetradecane	5.6	(42)	227	(54.3)	0.763	Useful in mixture with higher melting point
Hexadecane-tetradecane mix	10	(50)	–		0.77[c]	Commercially available?
Dioxane	12	(53)	146	(34.8)	1.03	Water miscible; peroxides formed if exposed to air or not frozen or not wet.
Water-dioxane mix						
0.6% water	9	(48)	–	–	1.03[c]	Wet mixture – avoids peroxides
3% water	6	(43)			1.03[c]	Wet mixture – avoids peroxides
15% water	2	(36)			1.03[c]	Wet mixture – avoids peroxides

[a] Data source: http://webbook.nist.gov/chemistry/.
[b] At 25°C. Data source: http://www.sigmaaldrich.com/Brands/Aldrich.html.
[c] Calculated value.

refrigerants to facilitate wrapping around the temperature logger. Materials were stored in the containers at temperatures below their respective melting points for 72 h prior to being placed in insulated boxes and monitored until the material thawed and warmed to near room temperature. Temperatures were monitored with Hobo® temperature loggers that were surrounded by the bags of frozen material.

In the second set of laboratory tests, additional comparisons were made with the more promising compounds. The water-dioxane mixtures (15%, 3%, and 0.6% water) and the hexadecane-tetradecane mixture were compared side-by-side. The water-dioxane mixtures were in the same plastic bag containers as the previous materials. The hexadecane-tetradecane mixture was purchased and tested in a polyurethane bag as supplied by the manufacturer. All other compounds were prepared and placed in the polyethylene bags in our laboratory. These four materials were frozen at -1°C for 72 h then placed in a controlled temperature chamber at 25°C. Temperatures were again measured with Hobo® temperature loggers wrapped with the bags of frozen material.

Two-Compartment Shipments

The two-compartment container developed by Biotactics, Inc. (Perris, Calif.) was used for overnight test shipments. It was a 2.5-cm thick EPS container enclosed in a corrugated cardboard box (outside dimensions 36 cm × 26 × 26 cm high). There was 2.5-cm thick foam packing material covering the bottom of the container and at the top. The interior was divided into two compartments using another layer of 2.5-cm thick foam packing material. The upper compartment contained the gel pack and the lower compartment contained beneficial insect vials and additional temperature sensors. A small gap in the foam dividing the two compartments allowed the appropriate amount of cooling of the lower compartment to maintain the proper temperature of the insect vials. Temperatures throughout these two containers were recorded during overnight air shipment from Perris, California to Manhattan, Kansas.

The beneficial insect vials were 8.3- × 3.8-cm inside diameter plastic, 0.13-cm wall thickness, with screw-on lids and were two-thirds full of the carrier media but did not contain beneficial insects. The media was corn cob grits, which is used for predatory mites. Typically, each vial of this size would contain about 200 beneficial insects or about 1000 predatory mites.

A Hobo® temperature logger (Onset Computer Corp., Bourne, Mass.) recorded the compartment temperature, and another Hobo® with an external sensor recorded the temperature outside the EPS box. The ambient temperature outside the cardboard box was calculated from this exterior temperature. The temperature in the vial was also recorded by a Hobo® data logger with an external temperature sensor. The target vial temperature during shipment was 10°C. Two containers were assembled in a controlled temperature room at approximately the target temperature and then sent through normal overnight shipment via Federal Express®.

Insulation Requirements

The theoretical required thickness of insulation and mass of refrigerant were determined based on heat loss calculations (eq. 2) using a Microsoft Excel spreadsheet for three types of containers:

- The standard single compartment container with EPS insulation (R per unit thickness = 29 m · °C/W) (ASHRAE, 1989), uniform interior temperature of 10°C, and the sample surrounded completely by refrigerant.
- A single compartment container with superior insulation — higher thermal resistance and higher cost — (R per unit thickness = 52 m · °C/W), uniform interior temperature of 10°C, and the sample surrounded completely by refrigerant.
- A simplified two-compartment container similar to that used in the test shipments. This arrangement did not include the additional foam packing above and below the sample that would provide extra insulation, but did include different interior temperatures in the two compartments. Eliminating the extra foam made it possible to compare directly to the calculations for the single-compartment containers that do not have foam. Seventy percent of the interior volume, i.e., the sample compartment, was at 10°C and 30% was at 0°C. (Separate calculations were made with the foam included for comparison, but complete graphs are not shown for that special case.)

Additional thermal resistance was included for air film resistance (R = 0.125 m^2 °C/W) on two-thirds of the box exterior, assuming one-third was not exposed to air; the corrugated fiberboard box (R = 0.064 m^2 °C/W); a 3-mm air

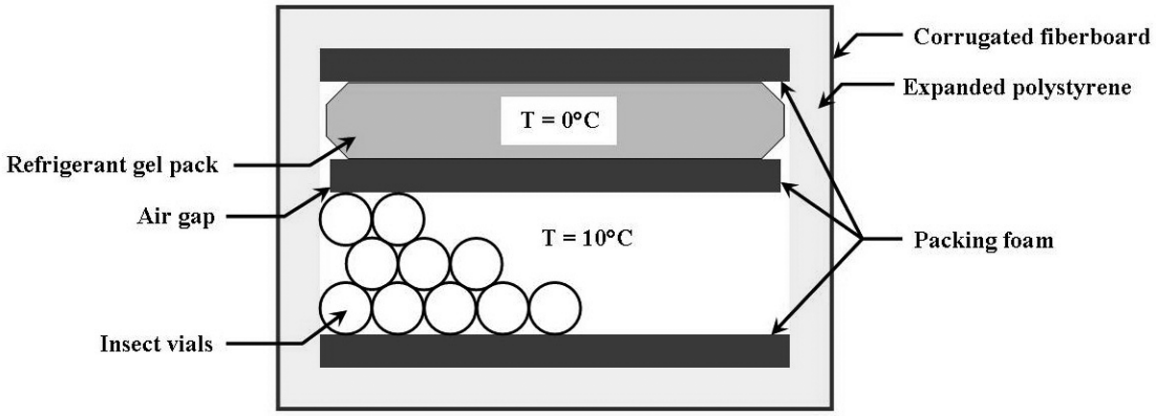


Figure 2. Cross-section of two-compartment container (not to scale).

space between the fiberboard box and the insulation material (R = 0.13 m^2·°C/W) over 70% of the total interface area; and interior air film resistance (R = 0.125 m^2·°C/W) only under the top surface of the box interior. All thermal resistance values were based on ASHRAE (1989).

The effective area of the container was calculated as the log mean average of the inside and outside surface areas to minimize potential errors from corner effects. Three sizes of containers were evaluated covering the typical range of shipping container sizes used in the industry, with inside dimensions as follows: (a) small, 28.3 × 18.8 × 18.8 cm, interior volume = 0.01 m^3; (b) medium, 36.8 × 24.4 × 24.4 cm, interior volume = 0.022 m^3; and (c) large, 47.9 × 31.8 × 31.8 cm, interior volume = 0.048 m^3. The inside dimensions of the containers were constant in the calculations, and the outside dimensions increased with increasing insulation thickness.

Results and Discussion

Laboratory Tests – Natural Refrigerant Alternatives

Preliminary evaluations of the freezing characteristics were based on the first set of laboratory tests with 200-g samples. The data logger temperature history was obtained with dioxane, benzene, glycerol, and the water equivalent gel pack in these tests. Glycerol results were not useful because it super cooled instead of freezing; the other results are shown in figure 3. The solvents p-Xylene and t-Butanol were eliminated based on fundamental considerations indicated in the comments in table 2. The hexadecane-tetradecane mixture was already known to have good freezing characteristics and was not tested until the second set of tests with the more promising options. The properties in table 2 show the range of melting points provided by these materials was expected to be approximately 6°C to 18°C. The data logger placement inside the containers matched the vial placement in the overnight test shipments, so the recorded temperatures represented vial temperatures, corresponding to those in the test shipments.

For dioxane (fig. 3; melting point 12°C) the logger temperature averaged slightly more than 2°C higher than the published melting point during the stable period (approximately 6 h). For water and benzene, the logger temperature was also 2°C higher than their published melting point during the stable period. Benzene did not perform well, showing less consistent temperatures and a shorter stable period than the other refrigerants. Dioxane showed the second longest stable period after water, which has a much higher heat of fusion than the other refrigerants (table 2), and maintained the logger temperature at 4°C above the 10°C target.

The results in figure 3 show the major advantage for water — a high heat of fusion, giving a longer stable period for the same mass of refrigerant. Water's major disadvantage is also seen — the freezing point is too low; the temperature maintained during the stable period was 8°C below the target temperature. However, these observations suggested that a mixture of dioxane, with a high melting point, and water, with a low melting point, should be attempted in subsequent tests to obtain the target temperature. Other observations are noted under the comments in table 2.

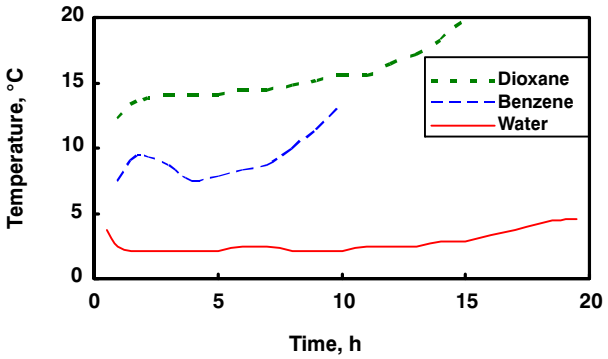


Figure 3. Vile temperatures from first set of laboratory trials with refrigerant compounds.

The results of the second set of laboratory tests are shown in figure 4. Of the water-dioxane mixtures tested, the lowest concentration of water (0.6%) produced the best temperatures in this set of laboratory tests. Good lengths of the stable temperature period were also observed in these experiments with this low concentration, slightly exceeding those of the hexadecane-tetradecane mixture. The 0.6% water-dioxane mixture held a temperature near the 10°C target for 25% longer than the hexadecane-tetradecane mixture. These results showed that the water-dioxane mixtures can be adjusted for different melting points around 10°C and the 0.6% water-dioxane mixture was the most effective mixture tested.

The hexadecane-tetradecane mixture should also allow for fine-tuning of the melting point by varying the proportions in the same manner, although other proportions were not tested. The observed stable period of the tested mixture was shorter than that of the dioxane-water mixtures. Binary mixtures of these organic solvents form nonvolatile crystalline structures upon freezing and melt over a range of temperatures rather than at a specific temperature point like pure substances; the width of this temperature range can vary widely depending on the specific solvents and relative concentrations (Levine, 1995). Determining the freezing properties and kinetics of freezing was not in the objectives of this research and those items were not investigated. For the hexadecane-tetradecane mixture the kinetics of freezing combined with the properties of the mixtures resulted in the slowly increasing temperature rather than the extended period of stable temperature seen for the dioxane-water mixtures (fig. 4).

Overall, the 0.6% water-dioxane mixture and the hexadecane-tetradecane mixture performed well in testing

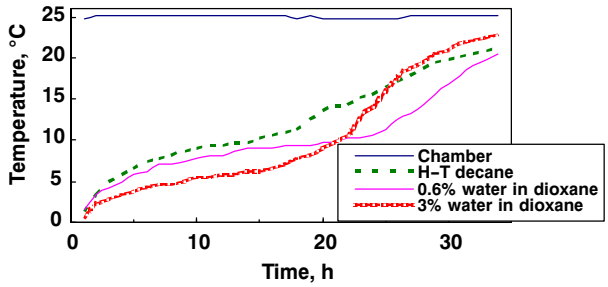


Figure 4. Comparison of three natural refrigerants in the controlled temperature chamber.

and appear to have minimal drawbacks. They showed good, adjustable, melting points and reasonable lengths of the stable period with the 0.6% water-dioxane mixture having the better length of the stable period.

Two-Compartment Shipments

The temperatures measured during the two-compartment shipments are shown in figure 5. Results shown are for two containers (designated A and B) shipped at the same time by overnight express shipping. The ambient (exposure) temperatures for these two containers averaged approximately 21°C. These exposure temperatures ranged from 16°C to 28°C, which provided a moderate range of conditions for the refrigeration system. However, in hot summer weather, exposure temperature spikes above 40°C would be expected. Under the test conditions, the temperature inside the vial remained close to the target of 10°C with relatively small temperature increases appearing when the ambient temperature spiked. At the maximum ambient temperature, 28°C, the average vial temperature was 3.4°C above the set point temperature if a 15-min delay is assumed for the interior temperature to respond to changes in ambient conditions. This relationship between deviation from the set point and the difference between ambient temperature and set point was evaluated for the entire test.

Figure 6 shows the set point deviations plotted against the difference between that set point temperature (10°C in this case) and the ambient temperature. The data shown are with interior temperatures tabulated after a 15-min time delay, which allows time to respond to the exterior temperature. When the exposure temperature was at its maximum, 28°C, the vial temperatures deviated from the set point by 3.4°C. The deviation from the set point would be 7.7°C when these data are linearly extrapolated to an ambient exposure temperature of 40°C (corresponding to a temperature difference of 30°C) using the equation shown in figure 6.

Results for the second container shown in figure 5 were very similar to the first, with the temperature inside the vial again staying near the target of 10°C. Figure 7 compares the exposure temperatures for the two containers. The estimated stages of shipment are shown on the figure along with labels of the points where the containers were being loaded. It is at the loading points that containers are exposed to existing weather conditions causing temperature spikes in the summer, sometimes compounded by solar heating. These temperatures indicate that these two containers were separated somewhat during the journey as they often were exposed to different temperatures. The average exposure

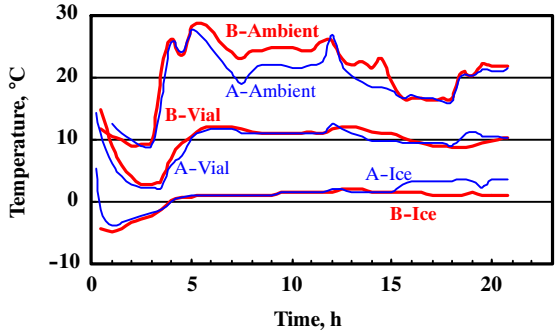


Figure 5. Temperatures during two-compartment shipments for the two packages, "A" and "B" (average exposure temperature = 21°C).

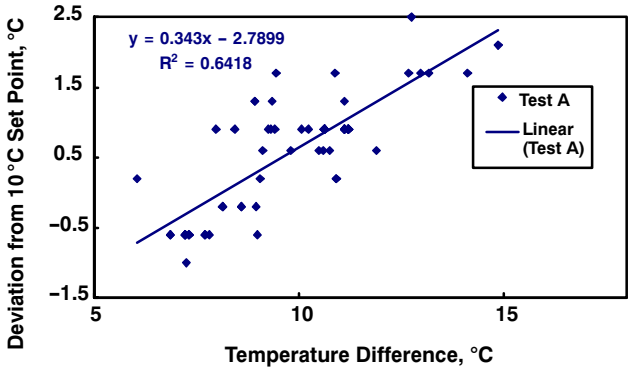


Figure 6. Example correlation of set point deviation to difference between set point temperature and exposure temperature (15-min lag time for interior temperatures).

temperatures were about 20.1°C and 21.8°C for containers A and B, respectively. Both container interior temperatures were nearly equal (fig. 5). This two-compartment container performed very well under these conditions. Vial temperatures stayed near the middle of the desired range, 5°C to 15°C, throughout the shipment, which indicates that even larger swings in exposure temperature could have been tolerated without causing excessive deviation in vial temperatures.

Insulation Requirements

Based on heat loss calculations using equation 2, figure 8 shows the calculated mass of refrigerant required for three container sizes to maintain 10°C for 30 h for three different exposure temperatures. These results showed the diminishing benefit of insulation as the thickness increased. There is little benefit from additional insulation over 6 cm at the lower exposure temperatures while the higher exposure temperatures continue to benefit up to slightly greater thicknesses.

Figure 9 shows results calculated for the single-compartment container with higher thermal resistance insulation than the standard EPS insulation used for figure 8. The required refrigerant mass was noticeably improved with the better insulation material; it was reduced by 37% with 2.5-cm insulation thickness and 40% when there was 5 cm of insulation for all container sizes. The improved insulation may prove worth the extra expense since both the mass of refrigerant and the cost of shipping (for a reduced weight)

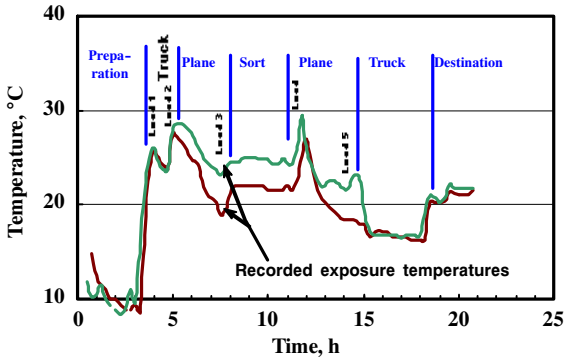


Figure 7. Ambient (exposure) temperatures during overnight shipment of two-compartment containers.

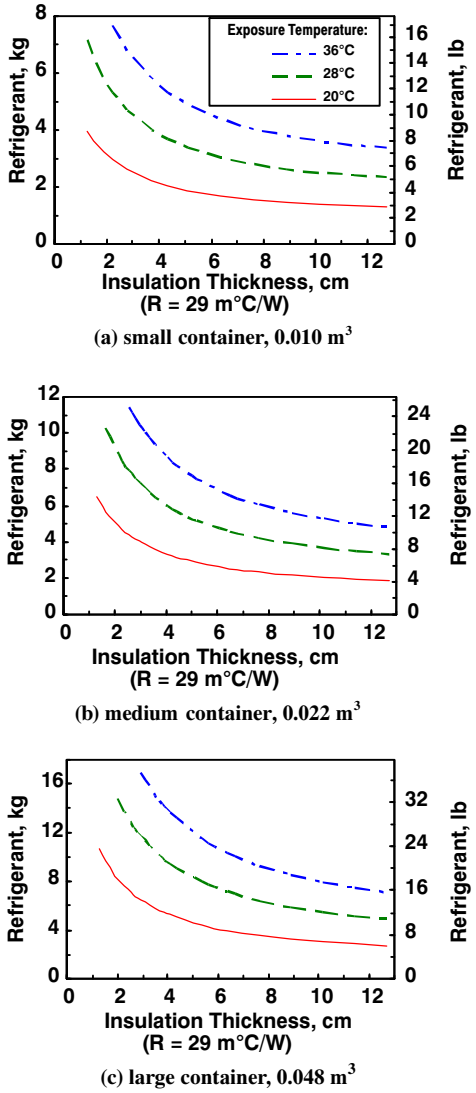


Figure 8. Refrigerant requirements for single-compartment container with 0.6% water in dioxane refrigerant and standard EPS insulation.

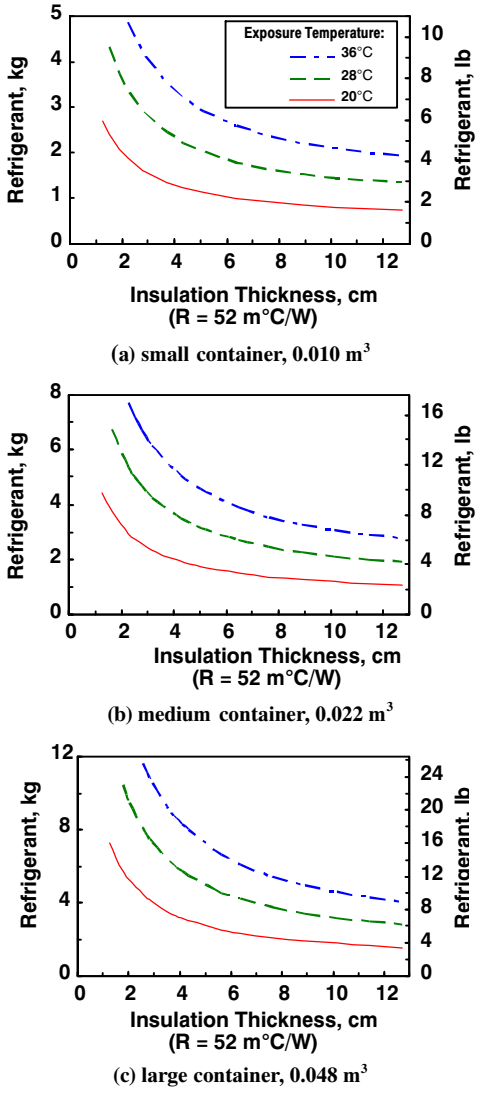


Figure 9. Refrigerant requirements for high thermal resistance single-compartment container.

will be reduced. Shippers can use these graphs to determine the most economical method in their unique situation based on their material and shipping costs.

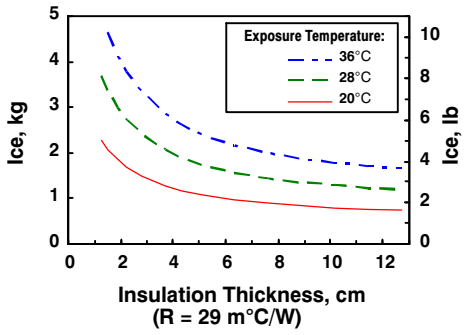
Figure 10 shows comparable results calculated for the simplified two-compartment container similar to that used in the test shipments, but without the additional foam packing above and below the sample. The refrigerant was water. A similar improvement in mass of refrigerant required was seen with this container using water, with a higher heat of fusion, as was seen with the better insulation material used with the water-dioxane mixture in figure 9. The reduction in required mass was 43% for both the 2.5- and 5-cm insulation thicknesses for all container sizes.

The same trends were evident as with the other containers and additional insulation beyond a thickness of 5 to 6 cm at the lower temperature, and slightly great thickness at the higher temperatures, did not appreciably increase the refrigeration effectiveness. These calculations were specifically based on water as the natural refrigerant, but they can also be applied to other natural refrigerant mixtures or the common gel packs that have approximately the same heat of fusion as water. Shippers can evaluate many common scenarios with these graphs to determine the best design fortheir use. The spreadsheet model can be used for comparison of other useful variations as needed by shippers.

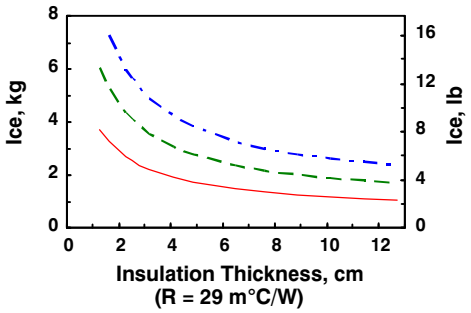
Separate calculations were made for the two-compartment container with the upper and lower foam layers included to quantify the reduction in required refrigeration mass due to the additional insulation effect from the foam. In those calculations, the difference averaged 19% reduction of required mass with 2.5 cm of EPS insulation and 12% reduction with 5 cm of EPS insulation. There was little variation between the three container sizes; the maximumdifference in the percent reduction between the container sizes was 0.7 percentage points for those two common insulation thicknesses.

Summary and Conclusions

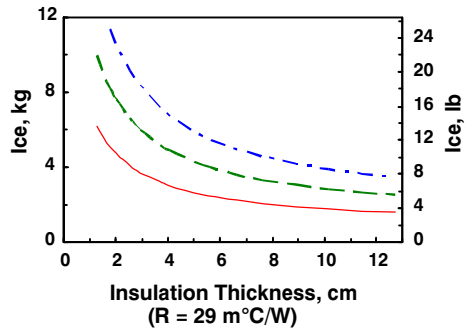
Heat transfer in beneficial insect shipping containers was evaluated theoretically with a steady state heat transfer analysis and experimentally with overnight shipments and in the laboratory. The fundamental approach considered was to



(a) small container, 0.010 m^3



(b) medium container, 0.022 m^3



(c) large container, 0.048 m^3

Figure 10. Refrigerant requirements for a simple two-compartment container using water for refrigerant and standard EPS insulation.

use a natural refrigerant to balance heat gain for 30-h shipments. Specific conclusions from these studies were:

- The two-compartment container was effective at maintaining the desired temperature during fall shipments.
- The 0.6% water-dioxane mixture and the hexadecane-tetradecane mixture had the best results of the new solvents evaluated, with correct melting points and good lengths of the stable temperature period. Of the two solvent mixtures, the 0.6% water-dioxane mixture was superior based on the length of the stable temperature period.
- The refrigerant requirements and the tradeoff between refrigerant mass and insulation thickness may be determined from the figures presented. The heat transfer model can also be used to determine requirements for other refrigerant and insulation configurations.

Both the two-compartment container with the frozen ice gel and the single-compartment container with the frozen 0.6% water-dioxane mixture maintained the desired temperature range during testing. The two-compartment ice gel container has the advantage that it does not require the use of a solvent. It also requires less mass of refrigerant, which results in lower shipping cost. The only apparent drawback is that this two-compartment container has not gained acceptance among producers other than the container originator, apparently due to the difficulty of implementing the precise arrangement of materials in the container. The advantage of the 0.6% water-dioxane mixture is that it only requires a very simple packing arrangement.

Chemical Cost and Safety Factors

Dioxane, is a bulk industrial solvent and costs ca. $30/L. It is miscible with water and the temperature range over which it exists in the liquid phase is about the same as that of water. It is classified by the International Agency for Research on Cancer (IARC) as a Group 2B carcinogen: possibly carcinogenic to humans. Upon standing it forms peroxides that can explode when concentrated, such as during distillation. These are non-factors in the current application, because the dioxane is kept in sealed, solvent resistant non-permeable, poly bags. In our labs, the dioxane in the pouches was stable for more than two years. The alkanes cost more than $100/L. Hexadecane (boiling point 287°C) ignites easily under compression, and has been assigned a Cetane Number of 100 and is a reference for comparing the ignitability of other fuel mixtures

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