Modeling Air Transportation of Fresh Seafood

by

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(ABSTRACT)

Several factors related to the proper shipping of fresh seafood by airplane were studied in this thesis. These included precooling, gel pack effectiveness, external temperatures encountered by shipping containers, and coolant placement in a shipping container.

Experiments were conducted to determine cooling times of 10 and 20 pound boxes and 10 pound bags of whole fish. The "10-pound" box was then modelled using finite element techniques. The model was found to accurately predict the temperature response of the box for a constant temperature boundary condition. Different boundary conditions were applied to the model. These were: constant temperature (such as an ice-slurry); low, medium and high velocity air (such as in a commercial refrigerator). The model was then used to predict cooling times for the other boundary conditions.

The enthalpy needed to thaw the contents of different gel packs was measured and compared to that of ice. None of the gel packs had as high an enthalpy as ice. In addition, the warming characteristics of the gel packs with the highest enthalpy was compared to those of ice. It was found that the warming characteristics of the gel pack appeared to be similar to that of ice.

The actual shipment of seafood to distant markets was studied by sending a data logger with several shipments to the west coast and collecting temperature data every 5 minutes during these shipments. Temperatures in 12 different locations were measured. Of particular interest were the outside temperatures which were later used in the modeling of the shipments.

The shipments were sent in EQ containers. The containers experienced a wide range of temperatures.

A finite element model was developed to predict the temperature of seafood under simulated transport conditions. Two boundary conditions were applied to the model; these were still air at 30°C and the approximate temperatures encountered during one of the shipments. Three different arrangements of coolant placement were studied. These were all ice on top of the product, half the ice on top and half in a layer in the middle of the product, and half of the ice on top of the product and half of the ice below the product. The latter arrangement provided the most uniform temperature distribution of the three through 18 hours of simulation. It was also found that shipments should be delivered in less than 24 hours for the amount of coolant used.

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Chapter 1

Introduction

On the average, every American consumes more than 15.2 pounds of seafood per year (U.S. Department of Commerce). There has been a dramatic increase in consumption of seafood in the United States as well as the rest of the world over the past 10 years. This increase is likely due to an increased concern among people to eat healthier foods. Seafood is considered to be healthier than both beef and pork. This increased consumption of seafood has also led to an increase in the demand for fresh seafood. Fresh seafood can be differentiated from frozen seafood in that it may not be frozen in part or wholly at any time prior to its purchase. Fresh seafood is often in demand in locations distant from the coasts of the United States. In addition, there is also a special demand for Atlantic and Chesapeake Bay varieties in markets as far away as the West Coast. This new demand has generated a problem that the seafood industry has not encountered previously: delivering a high quality fresh product to a market that cannot be reached in a reasonable time using traditional transportation methods. As a result, producers are turning more and more to air transportation to deliver their fresh seafood to market.

Air transportation has one major advantage over transportation by refrigerated truck. Refrigerated truck transport is limited in the distance it can service due to the amount of time required to drive to some markets, as in the case of trans-continental transport. For markets that cannot be reached by truck in a reasonable amount of time air transportation is the only feasible alternative form of transportation.

It has been estimated that up to 5 million tons of product are lost each year in the seafood industry; a large proportion of this loss can be contributed to spoilage of product by microorganisms (Wheaton and Lawson, 1985). The primary factor responsible for the loss of quality in fresh seafood transportation and storage is poor temperature maintenance.

Holding temperatures are very important, because even small changes in temperatures can greatly affect the quality and shelf-life of seafoods. The type of microorganisms which comprise the microbial population of seafood is determined, to a large extent, by the harvesting location and the season. Bacterial populations of seafood are most often psychrotrophic. The most common bacteria isolated from most types of seafood include members of the genera: *Pseudamonas*, *Moraxella*, *Acinetobacter*, *Alteromonas*, *Flavobacter* and *Vibrio* (Hoff, *et al.*, 1967 and International Commission on Microbial Specifications for Foods, Vol. 2, 1980).

Four major physiological groups of bacteria may be distinguished by their temperature ranges for growth: thermophiles, mesophiles, psychrophiles and psychrotrophs. Of these groups, psychrotrophs are the most important when considering air transportation of fresh seafood. Psychrotrophs have a minimum growth temperature of -5 to 5°C, an optimum growth temperature of 25 to 30°C, and a maximum growth temperature of 30 to 35°C. (International Commission on Microbial Specifications for Food, Vol. 1, 1980).

Temperature has a pronounced effect on the growth of bacteria. Bacteria grow faster at their optimum temperatures and even small temperature decreases can greatly slow growth (Ingraham, 1958). For example, Ingraham demonstrated that if the generation time (the time for the viable population to double) of a psychrotrophic bacteria is 30 minutes at 25°C, it will be 75 minutes at 20°C, 120 minutes at 15°C, 200 minutes at 10°C and 1200 minutes at 0°C. As spoilage is to a large extent a function of bacterial growth, and seafood will generally spoil between 1 million 100 million cells per gram, then it is obvious that the initial population and generation time are critical factors in determining shelf-life and quality. As an example, if finfish fillets have an initial population of 10,000 bacteria per gram and are spoiled at 10 million bacteria per gram, then the expected shelf-life can be determined using the above generation times. It will take 10 generations to reach a spoilage level of microorganisms in the fillets. Therefore, at 0°C the shelf-life would be 8.3 days, at 5°C the shelf-life would decrease to 2.6 days and at 10°C the shelf-life is only 1.4 days.

Fluctuations in temperature are also very important to the shelf-life. If the fillets were initially at 25°C and held at this temperature for only 2 hours and then cooled to 0°C the shelf-life would drop from 8.3 days to 5 days. If it had been held for 3 hours the shelf-life drops to 3.3 days/ In this example the concept of pre-chilling is brought out. The idea that product should be chilled as quickly as possible prior to shipment to keep the initial count of microorganisms as low as possible.

To control temperature one must have some knowledge of the overall transportation process. However, little is known about the environmental conditions to which seafood is subjected during air transport. Therefore, it is difficult for a processor to know what to expect while his product is in transport to market.

In air transportation there are many methods of packaging currently being used by processors. A brief description of the most common practices is summarized here. The most common weight of seafood shipped is 60 to 100 pounds. however, shipments as large as 10,000 pounds or as small as 25 pounds occur. The most common package used to transport fish by air is the EQ container. It is designed to carry between 80 and 120 pounds of seafood, the norm being 100 pounds of seafood plus the coolant. The seafood may be packaged in polyethylene or metal boxes each holding 10 or 20 pounds or may be packaged in plastic bags holding 10 pounds or may be shipped in bulk. The metal containers are being phased out of use. These smaller packages are placed inside the EQ container after the container has been lined with a plastic bag and 3/4-inch insulation made of polystyrene. The polyethylene boxes will provide the best seafood upon arrival in general as the shock of handling will have little effect on them. Once the seafood is placed in the EQ container a coolant is placed on top of it, although some may place coolant on the bottom as well or in layers. Layering may have the best effect when seafood is shipped in bulk. The package is then closed and taped shut with packaging tape and taken to the airport for shipment.

A container may encounter very different conditions during air transportation for different shipments. Some of the possible scenarios are given below. They are not actual shipments, but are based on experiences some processors have encountered.

From Hampton, VA processor A may want to send a shipment to Los Angeles, CA. In order to make the trip to L.A. the airline must ship A's shipment to Charlotte, NC, then to Phoenix, AZ, because no direct flights are available. A drops his shipment off at the airport at 10:00 AM and it is placed on a 3:35 PM flight to Charlotte. It arrives in Charlotte and the handlers notice that it says on the package to refrigerate if possible, so they place it in a floral refrigerator set at 45°F. The package remains in storage for twelve hours until being loaded onto an airplane for Phoenix. During the flight the temperature in the storage area drops to 45°F. It arrives in Phoenix at 2:00 PM EST. Upon arrival it is immediately loaded onto a flight for L.A., but the flight does not leave until 5:00 PM EST. As the package sits in the storage compartment the temperature rises to 90°F. Finally, at 7:00 PM EST 33 hours later it arrives in Los Angeles.

Processor B wants to ship a seafood package to Monterey, CA. He also delivers his package at 10:00 AM to the airport in Hampton, VA. There is a flight to San Francisco at 11:00 AM on which the package is placed. It arrives in San Francisco at 4:00 PM EST and is placed immediately on a truck headed for Monterey and arrives there shortly after 5:00 PM EST only 7 hours after being delivered to the airlines.

Processor C wants a seafood package delivered to Las Vegas, NV. He also delivers his shipment to the airline in Hampton at 10:00 AM. This shipment must also be routed through Charlotte and Phoenix. It follows the same course as the first shipment until it reaches Phoenix. It is left on the plane by mistake and misses the flight to Las Vegas. The next flight is not for 18 hours, but the airlines knows if it can deliver the package in 48 hours they have completed their part of the shipping agreement, so they wait and ship it on that flight. During the wait the box is placed in a storage area which is not temperature controlled and during this very hot day the temperature reaches 100°F inside, but drops later in the day to a low of 80°F in the evening. It is loaded onto the airplane and arrives in Las Vegas at 9:00 AM EST 47 hours after shipment. All product inside is in an unsellable condition.

From the above discussion, several factors that affect the success of a shipment of fresh seafood can be identified. These include the amount of time required for the shipment to reach it's destination, the amount and placement of gel packs, the amount and type of insulation, the manner in which the product is packaged, the thermal environment to which the container is subject, and the handling of the container during shipment. The purpose of the research reported on in this thesis was to investigate some of these factors so that recommendations for improvement of shipping methods could be formulated.

1.1 Objectives

The objectives of this research were:

1. to estimate the amount of time needed to cool fish in a "10-pound" box,
2. to model cooling of fish in a "10-pound" box using finite element analysis,
3. to use this model to estimate the cooling time for various boundary conditions,
4. to determine the effectiveness of one type of gel pack and compare this to the effectiveness of ice,
5. to measure the range of temperatures seafood packages may encounter during transportation,
6. to develop a thermal model of a fresh seafood shipping container, and
7. to examine model behavior due to three different coolant placements.

Chapter 2

Review of Literature

The literature published on air transportation of fresh seafood is limited. Wheaton and Lawson (1985) published a near comprehensive treatise on handling and processing of aquatic species and food products, but only briefly discussed shipment of fresh product. Martin and Flick (1990) also published a comprehensive work on the seafood industry. A chapter was included on the transportation of product to market. This chapter included refrigerated truck transport, non-refrigerated truck transport and air transport. It is pointed out that product must be maintained at a temperature below 45°F (7°C) and a temperature below 5°C is preferable. Most of this text is a replication of material covered in the NFI and ATA report discussed below.

Barnett (1988) discussed the horrors some processors have encountered in trying to transport fresh seafood by air. She gave several practical suggestions for avoiding these problems. One important publication is *Guidelines for the Air Shipment of Seafood* (National Fisheries Institute and Air Transport Association of America, 1987). This manual is particularly lacking in the area of technical information. There is no information on expected temperatures that a seafood container may be expected to encounter. There is no information about the quality and efficiency of the numerous gel packs on the market. There is no information about the possible amounts of gel packs that may be needed in order to ensure product integrity. There are, however, practical facts for shippers, handlers, and packaging manufacturers. Two concerns addressed are: that all people involved in air transport need to work together so that a shipment will arrive in good condition, and that good communication between air carriers and the seafood processors must exist. This manual also contains information on acceptable methods of packaging, packaging design, coolants, and several important handling and packaging procedures.

Wagner, *et al.* (1969) described a container specifically developed for shipment of fresh fish. The shipments were made by unrefrigerated truck to 3 locations from 150 to 700 miles from the processing location of Gloucester, MA. The cities selected were Burlington, VT, 175 miles away; Syracuse, NY, 355 miles away; and Pittsburg, PA, 655 miles away. A total of 10 weekly shipments were made to each location. Each shipment consisted of two or three 25-pound tins of fresh fish cooled for 48 hours to 33°C and then packed into the BCF (Bureau of Commercial Fisheries) container. The BCF container consisted of a cardboard box lined with a plastic bag and 2 inches of polystyrene insulation. The shipments were packed in 24 to 30 pounds of ice frozen in polyethylene bottles or in 10 to 15 pounds of crushed ice with a slab of uraformaldehyde foam to absorb moisture. The longest time a shipment took to arrive was 77.0 hours. All product arrived in fair condition, but most shipments arrived in very good condition. The conclusion was that seafood could be shipped as far away as 700 miles by unrefrigerated truck if proper packaging procedures were followed.

Chattopadhyay and Bose (1972) investigated the placement of ice in shipping containers to minimize temperature rise in the containers. Their goal was to keep fish cool for 72 hours, during which time the fresh fish would be delivered from processor to market via train. In these studies fish at 5°C were packed with an equal quantity of ice in an insulated shipping carton made of plywood. The insulation was made of polyurethane with a thickness of 1 cm. Three ice placements were studied. Each had five layers of either fish or ice. The second and fourth layers had one-half of the fish each in all cases. In the first shipment the top and third layers contained each a fourth of the ice and the bottom layer had half of the ice. In the second shipment three-eighths of the ice was in the top layer and another three-eighths of the ice was on the bottom and the third layer contained the remaining fourth of the ice. In the last shipment the bottom and third layer contained one-fourth of the ice each and the top layer had half the ice in it. After 22 hours it was found that the temperature had reached 13°C at the midplane in the top of the container in the case of the third ice placement. All other ice placements had a higher temperature after 22 hours. This study indicated that the last ice position was the best.

Rosane (1986) studied the air transportation of live shellfish. She modeled the shellfish by filling surgical gloves with a water and sodium chloride solution of 13.25% by weight sodium chloride. This provided a thermal mass close to that of the actual shellfish. Heat flow was measured using sensors and temperature of the thermal mass was measured over time. She then validated her results with the mathematical model developed by Chattapadhyay and Bose (1969). She encourage sub-cooling of the product. With shellfish this is practical, because their mobility is diminished and they remain viable down to 2°C.

Crapo and Paust (1986) studied air shipment of fresh fish in Alaska. They discussed the importance of maintenance of low product temperature to deter microbial spoilage. They found that if fresh fish is maintained at 32°F the product would remain in sellable condition for 10 to 14 days depending on the species. They also discussed the use of pre-chilling of product and found that blast-freezers will damage the product, because the external layers of the fish will be cooled below freezing while the internal temperature remains high. The use of ice-water slurries was encouraged in pre-chilling, but noted that in this case product must be dried prior to packaging. They stated the following rules for fresh fish transportation: keep it cool, keep it clean, and keep it moving.

Modeland (1989) outlined the risks of microbial damage associated with transport of fresh fish from the point of capture to the table.

In addition to these studies of seafood transportation a study was conducted to look into spoilage of fresh fish by Cook and Ruple (1989).

Though sparse, the literature points out several important factors. The shipments need to be cooled as much as possible prior to shipment. The shipments may also be expected to encounter extreme temperatures and poor handling by airport personnel. This was experienced in the course of this research when a shipment was sent to Los Angeles from Hampton. The shipment was received in such poor condition that one of the sides was almost completely missing and the product was leaking out. All temperature data had been lost because of leakage of blood and water into the data acquisition section of the package. Also the shipments need to be well insulated with sufficient coolant to last until arrival at their destinations. Conversations with personnel at Piedmont Airlines indicated that all shipments are guaranteed to arrive within 48 hours.

There is a lack of thermal properties data available for fresh seafood. While much is available for frozen seafood these properties would not be appropriate for fresh seafood due to the change in the thermal properties of water as it changes phase. In addition, the properties available are only for a few species of fish, specifically cod and salmon. The data available usually are not referenced as being for fish muscle or whole fish (Wheaton and Lawson, 1985). In modeling anything it is critical that the model have appropriate properties. For heat transfer the important properties are the density, thermal conductivity, and specific heat. These values or the methods for finding them were found in several references. These will be noted in this thesis when appropriate.

Chapter 3

Theory

The differential equation of heat transfer equation is:

$$k_x \frac{\partial^2 T}{\partial x^2} + k_y \frac{\partial^2 T}{\partial y^2} + k_z \frac{\partial^2 T}{\partial z^2} + \dot{q} = \rho C_p \frac{\partial T}{\partial t} \qquad [3.1]$$

This equation may be simplified by dropping the heat generation term and rewriting it in two dimensions. In that case it appears as:

$$k_x \frac{\partial^2 T}{\partial x^2} + k_y \frac{\partial^2 T}{\partial y^2} = \rho C_p \frac{\partial T}{\partial t} \qquad [3.2]$$

It may also be assumed that thermal conductivity is the same in both x and y directions. The term α is the thermal diffusivity and is defined as:

$$\alpha = \frac{k}{\rho C_p} \qquad [3.3]$$

where k is the thermal conductivity, ρ is the density, and C_p is the specific heat. Thus, [3.3] in two dimensions may be written:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad [3.4]$$

One encounters problems in solving this equation if the continuum does not have a simple shape, if the boundary condition is not homogeneous, or if the continuum is not made of a homogeneous material. In the case of the box of fish there are two distinct materials, the box made of polyethylene, and the contents which are fish. In the case of the shipping containers there are several materials: the box made of cardboard, the liner made of plastic, the insulation made of beaded polystyrene, the polyethylene boxes, the fish and the gel packs or ice. Due to the material non-homogeneity these differential equations must be solved numerically. Some common ways of approaching this problem include the finite difference technique and the finite element technique. The finite difference method takes the problem and breaks it down into many small parts and solves a simple difference approximation for each part. The finite element approach takes the problem and breaks it down into many small parts and solves an integral formulation of the problem for each part. The latter approach was used in this research. The general formulation of the finite element approach for heat transfer is summarized in Appendix A.

Chapter 4

Methods and Materials

The methods and materials and results and discussion in Chapter 5 will be presented in the same sequence as the objectives.

4.1 "10-Pound" Box Cooling Experiments

In order to accomplish the first objective, a series of experiments was conducted on "10-pound" boxes of fresh fish.

Ten pounds of whole Atlantic croaker (*Micropogon undalatas*) were packed into a "10-pound" polyethylene box. The "10-pound" boxes were obtained from the Container Corporation of Bedford, Massachusetts. The term *10-pound box* is widely used in industry. It is placed in quotes because in reality the box may or may not hold up to 10 pounds (4.5 kg) of fish or other types of seafood. A thermocouple probe was inserted into a fish that was located at the approximate center of the box. The thermocouple was connected to a data logger model CR10 (Campbell Scientific, Logan, UT) which recorded temperature in the fish every five minutes. The box with fish and thermocouple probe was then placed into an incubator at 30°C for 30 hours prior to cooling to insure uniform temperature throughout the box prior to cooling. The box was then placed into a cooler partially filled with crushed ice. More ice was packed on top of the box and the cooler lid was closed. The box was cooled in this way as an attempt to simulate constant temperature boundary conditions around the box. Icing is also a prechilling technique readily available to processors. This experiment was then replicated.

Tests were also conducted on "20-pound" boxes and "10-pound" bags. The methods for these tests were the same as for the "10-pound" boxes.

As the results will show the constant temperature boundary condition was not maintained. As the ice around the "10-pound" box melted, it was observed that an air pocket formed around the box, thus compromising the constant temperature boundary condition that was assumed. Another set of experiments were conducted to verify this using a gel made of a 1.5% cellulose gum and water and placed in ziploc bags. Each bag was filled to approximately the mass of a small croaker. The gel had for all intents and purposes the properties of water. Two different methods of cooling were tested. The first method was to place the "10-pound" box in a cooler of ice and allow it to cool as in the test on the fish. The second method included shaking the cooler every five minutes for the first hour and every fifteen minutes thereafter until the center temperature reached 0°C. These experiments were conducted three times for both cooling methods described above.

4.2 Finite Element Analysis of the "10-Pound" Box

In order to develop the finite element model for the cooling of the "10-pound" box, a series of tests were conducted to determine the physical properties of seafood. These properties were necessary for the model. The model was then developed for constant temperature boundary conditions. This model was then changed to examine various boundary conditions one may encounter cooling seafood.

4.2.1 Physical Properties Experimentation

The important physical properties for heat transfer analysis are density (ρ), specific heat (C_p), thermal conductivity (k).

4.2.1.1 Density

The *density* of any object is the mass of that object divided by its volume. For simple objects, such as a sphere or a rectangular prism, it can be easily calculated because the volume can be found without difficulty. For more complex objects, it is more difficult to calculate. In the case of this research, it was necessary to know the density of fish and polyethylene (the material the box is constructed from). For the polyethylene a value of 915 kg/m^3 was found in Loncin and Merson (1979). For the fish a value of 1075.0 kg/m^3 was found (Wheaton and Lawson, 1985). Experiments to find the density of whole fish were conducted because it was unclear whether the value found was for whole fish or for fish muscle. A method described by Mohsenin (1970) was employed. A fish was suspended by its tail from an Instron Model 1125 Universal Testing Machine. The weight of the fish in air (W_f^{air}) was measured. The fish was then lowered into a bucket of tap water and the weight was measured (W_f^{water}). Using a ratio of these two weights it was possible to calculate the specific gravity of the fish. The *specific gravity* is by definition the ratio of the density of a material divided by the density of water. Since the density of water is 1000.0 kg/m^3 the density of any material is 1000 times its specific gravity. Specific gravity is a dimensionless parameter. The specific gravity is:

$$\gamma_f = \frac{W_f^{air} + W_f^{H_2O}}{W_f^{air}} \qquad [4.1]$$

This test was run on two different species of fish, bluefish (*Pomatomus saltatrix*) and croaker (*Micrpogon undalatas*). The experiment was run on five different bluefish and four different croakers.

4.2.1.2 Specific Heat

The *specific heat* of a material is defined as the amount of energy required to raise the temperature of one unit of mass of that material one degree. In the SI system it is measured in *J/kg*·°C. For the polyethylene box a value of 2300 *J/kg*·°C was found in Loncin and Merson (1979). The specific heat value for the fish was reported by Wheaton and Lawson (1985) to be 3536.0 *J/kg*·°C. These values were used for all modeling.

4.2.1.3 Thermal Conductivity

The *thermal conductivity* of a material is defined as the ability of that material to transfer heat through it per unit time. Thermal conductivity may be a temperature dependent property, but was assumed not to be so in this research.

Loncin and Merson (1979) reported the thermal conductivity of polyethylene to be 0.32 *W/m·°C*. Most values for seafood found in textbooks were for frozen or frozen and then thawed seafood. This seemed inappropriate in this case, so it was necessary to conduct some experiments on fresh seafood to determine this value. At the time much of this research was being performed, Dr. Robert Kravets was developing a thermal conductivity probe at Virginia Polytechnic Institute and allowed tests to be run using his system.

The thermal conductivity of six species were tested using a method developed by Kravets and Larkin (1986). The following species were tested: flounder (*Limanda ferriginea*), whiting (*Merluccius bilinearis*), spot (*Leiostomus xanthurus*), sea trout (*Cynoscion regalis*), mullet (*Mugil cephalus*), and bluefish (*Pomatomus saltatrix*). For the bluefish three samples were taken. For all other species one sample was taken. Each sample was then placed in a small test tube and the thermistor probe was inserted into the muscle sample. The test tube containing the sample was then placed into a constant temperature bath. The sample was allowed to equilibrate for 60 minutes. The thermal conductivity was then measured 10 times and averaged at four different temperatures: 0°C, 10°C, 20°C, and 30°C.

4.2.1.4 Effective Thermal Properties

The volume of the "10-pound" boxes was found to be approximately 7000 ml. This was determined by placing a box on a scale and taring the box weight and then filling the box with water and weighing the amount of water required to fill the box. This weight divided by the density of water yielded the volume. The box held approximately 15.4 lbs (7.0 kg) of water. A fully packed "10-pound" box normally holds ten pounds (4.54 kg) of fish. The literature indicated that fish has a density between 2 and 8 percent greater than water. Assuming a density for the seafood of 1.075 kg/m^3 the box should contain 16.6 pounds (7.525 kg) of fish. The reason for this discrepancy was that there were air pockets between the fish in the box. Therefore, new "effective" physical properties would have to be estimated for use in the model. These new physical properties were estimated on a volumetric basis (Batty and Folkman, 1983). The following equation was used to define these properties:

$$v_{new} = \frac{V_{fish}}{V_{tot}} v_{fish} + \frac{V_{air}}{V_{tot}} v_{air} \qquad [4.2]$$

In equation [4.2] V_{fish} is volume the volume of fish, V_{tot} is the total volume the "10-pound" box holds, V_{air} is the volume of the air spaces in the "10-pound" box, v is the physical property of interest, and v_{new} is the new effective physical property. This equation was applied to density, specific heat, and thermal conductivity.

4.2.2 Development of the Finite Element Model

Finite element analysis takes a complicated problem and breaks it down into a finite number of smaller pieces which can be individually solved and then reassembles the continuum and gives an approximate solution for the whole problem. To have a correct model one must define properties, boundary conditions, and geometry properly. Having evaluated the physical properties, model formulation was initiated.

4.2.2.1 Model Geometry

The dimensions of the "10-pound" box were 73 mm by 268 mm by 383 mm. Due to the large difference between the depth (73 mm) and the length (383 mm) the box was assumed to be two-dimensional and was modeled as such. This is due to the fact that the heat transfer out of the top and the narrow side will influence the overall temperature of the box. For example, if the x-direction has a length of 268 mm, the y-direction has a length of 73 mm, and the z-direction has a length of 383 mm, then most of the heat will be transferred out of the two largest sides, the sides with length 268 by 383 mm and 73 by 383 mm.

The box also is close to rectangular. While it is curved on the corners, it has a flat top and bottom. For simplicity, the box was assumed to be a perfect rectangle with a length of 268 mm and a width of 73 mm and a depth that was infinite. The infinite depth is due to the assumption of two-dimensionality. The thickness of the polyethylene box was 1.5875 mm.

4.2.2.2 The Finite Element Model

The finite element model was developed with ANSYS Version 4.3a (Swanson Analysis Systems, Inc., Houston, PA) finite element software on a MicroVax II (Digital Equipment Corp., Maynard, MA) with the VMS 5.3-1 system. The model was designed as a perfectly rectangular box 73 mm by 268 mm. There were three different sizes of elements. The elements located in the corners were 1.5875 mm by 1.5875 mm. The elements on the edge of the box were 1.5875 mm by 3.8889 mm. The elements inside the box were 3.8889 mm by 3.8889 mm. The total number of nodes was 2142 with 2000 of elements. The applied boundary condition was a constant temperature boundary of 0°C. An initial condition of 30°C was assumed throughout the box.

This model was then used to determine the time required to cool the box for other boundary conditions that might be encountered in commercial practice. The model with the same initial conditions was subjected to convective boundary conditions to simulate how the box would react in a refrigerated room. Most refrigerators are maintained between 1 and 2°C. A temperature of 1.67°C was chosen since this corresponds to 35°F which is the approximate temperature maintained in commercial refrigerated storage. The convective heat transfer coefficients applied were 3.0, 10.0, and 76.0 *W/m*·°C which corresponds to still air, low velocity air, and high velocity air (Geankoplis, 1983).

The finite element model was also applied to the boxed gel for the experiments which were done to confirm that shaking the cooler would cause the boundary conditions to approximate a constant temperature of 0°C.

4.3 Gel Pack Heat Absorption Experiments

In *The Guidelines for the Air Shipment of Seafood* the following statement is made: "Under normal conditions, wet ice by itself will melt five times faster than chemical/gel type refrigerants." This statement seems to imply to the processor that ice will not work as well in the shipment of seafood as a gel pack. However, the statement is trying to encourage the processors to use gel packs, because they will melt slower than loose crushed ice. The guidelines do not mention hard, block ice of the same dimensions as a gel pack frozen to the same temperature as a gel pack.

An experiment was designed to investigate the thawing characteristics of similarly shaped and frozen gel pack and ice. A polystyrene cooler was used. A thermocouple was placed two inches above the bottom of the cooler. Hot wax was poured into the cooler to cover the thermocouple probe and allowed to cool and harden. The purpose of the wax was to provide a heat source from which heat would flow to encourage consistent thawing of the gel packs. The cooler was placed inside an environmental chamber set at 25°C and allowed to equilibrate. A gel pack was frozen to approximately -20°C and then placed directly over the probe in the cooler and the lid was placed over the cooler. The temperature of the probe was recorded every five minutes. Then the same was done with an equal weight of ice frozen in a ziploc bag. The gel pack tested was a "Kool-It" pack. This experiment was repeated three times for each material.

In addition to the method just described a differential scanning calorimeter was employed to determine the energy required to melt different gel substances. Their moisture content was also measured. These two tests were conducted at Texas A and M University by Dr. Vincent Sweat. In these test, small samples of gel were cooled to either -40°C or -10°C and then thawed. The energy required to melt the frozen gel was measured.

4.4 Air Transportation Temperature Measurements

One of the unknown parts of the air transportation process is the temperatures containers encounter during transport. As a container is moved from time of receipt to it's final destination, it may be placed in direct sunlight, an airplane cargo bay, refrigerated storage, or on a shaded loading dock. The thermal environment of these locations will determine the boundary conditions the container encounters which will ultimately determine the amount of energy lost to the environment during transport and the final temperatures in the container. To study this, a temperature collection system was developed to measure temperatures on the inside and outside of a seafood container while it was being transported.

A battery powered data logger (model CR10, Campbell Scientific, Logan, UT) and 12 thermistors were used for temperature recording and measurement. One thermistor was placed in the center of the mass of fish and two were taped to the outside surface of the container. The remaining nine thermistors were taped to the inside of the container insulation at various locations. Each thermistor was individually calibrated from 0 to 30°C. The calibration was used to develop quartic equations by statistical regression so that temperature could be calculated as a function of resistance. The thermistors had a resistance of 10KΩ at 25°C. Each thermistor was placed in series with a 10 kΩ resistor to form a simple voltage divider circuit. Then a 2000 mV voltage was sent through each circuit and the voltage across the 10 kΩ resistor was recorded. The voltage across the thermistor was thus:

$$V_T = 2000 - V_{10k} \qquad [4.3]$$

Then by simple electrical theory:

$$\frac{V_{10k}}{R_{10k}} = \frac{V_T}{R_T} \qquad [4.4]$$

This leads to:

$$R_T = \frac{V_T R_{10k}}{V_{10K}} \qquad [4.5]$$

The recorded resistances, R_T were later converted to temperatures through the calibration equations.

The circuits, along with the CR10 to which they were connected, were placed inside a "10-pound" box. This box was sealed as well as possible and placed on top of the mass of fish to be shipped which weighed approximately 100 lbs (45.4 kg). The fish were cooled to 0°C prior to packaging. Above the fish were placed 4 gel packs and below the fish 2 gel packs were placed. Each gel pack weighed approximately 1.78 lbs (.812 kg) each. This made the total mass of frozen gel approximately 10.7 lbs (4.9 kg). The data logger was set to record temperatures every 5 minutes. The container was shipped via Piedmont Airlines from Hampton International Airport to a distant location and then shipped back to Roanoke airport where it was picked up. The first two shipments went to Los Angeles and the third shipment to Phoenix. In the first shipment all data was lost because fish blood leaked into the box containing the data logger and short-circuited the power to the data logger.

4.5 Finite Element Model of the EQ Shipping Container

The cartons used in air transportation vary in size, shape and materials. A major method of package designation is by the weight of seafood it may carry. Packages are designated as E, EH, or EQ. E refers to a package holding up to 500 lbs. EH means it holds half an E container; that is 250 lbs. EQ indicates a package may hold up to a quarter of an E container or 125 lbs. In practice this package is seldom loaded above 100 lbs, however for handling purposes. For this research an EQ container was studied, because it is one of the more common container sizes used in shipment.

4.5.1 Model Geometry

The EQ container measures 44 cm by 56 cm by 76 cm. The outer envelope was made of waxed cardboard which is between 2 and 3 mm thick. Inside the cardboard was placed a plastic bag to prevent leakage. Inside the bag, 17 mm thick beaded polystyrene insulation was placed. This makes the thickness of carton, plastic and insulation approximately 2 cm. Inside the insulation the seafood was placed. It may be in "10-pound" boxes, "20-pound" boxes, "10-pound" bags, or lumped without protection. For this model the seafood was assumed to be placed in ten "10-pound" boxes, stacked in two rows five boxes high in the center of the container with an 8 cm air space on either side of the small ends and a 2 cm space from the larger side. Ice was placed on top of the seafood. The ice had dimensions of 4 cm by 36 cm by 56 cm. This corresponds to a mass of 1.237 kg (2.73 lbs). The amount of energy required to thaw this mass of ice is 424,500 J. There remained above the ice and below the top layer of insulation an air space of 8 cm. For simplicity it was again assumed that the "10-pound" boxes were rectangular.

4.5.2 The Finite Element Model

A finite element model was developed to attempt to predict some of the possible temperature extremes within a box during transport. The model was developed using ANSYS as described above. The EQ container modelled is photographed in Figure 1.

The finite element model was designed with elements of varying sizes. At the corners the elements were 2 cm by 2 cm by 2 cm. Along the edges the elements varied from 2 cm by 2 cm by 8 cm to 2 cm by 8 cm by 9 cm. Inside the box the elements were mostly 8 cm by 8 cm by 9 cm or 8 cm by 8 cm by 8 cm.

For purposes of determining if the mesh size used was small enough, the model was run using one continuous material for a time of five hours. The resulting heat flows for this model were plotted versus location. Temperatures were also plotted versus distance. The mesh was refined to include twice the nodes in the y-direction. The same heat flows and temperatures were plotted. The results show that while the more refined model yields a slightly smoother graph, the accuracy of the temperatures and the heat flows at individual nodes does not change. One major concern was that elements along the edge may experience excessive skewing which is warned against in Baran (1989) and other literature. Dietrick (1990) of Swanson Analysis Systems, Inc. said that so long as these plots did not differ significantly the results would be acceptable for the less refined mesh. He said that the caution about excessive skewing does not apply in cases where the major heat flow is through the narrow side of the elements as was the case in these models. These plots are shown in Appendix B.

The ice was modelled as having a constant temperature until it had absorbed enough energy to melt all the ice. After this, the ice was modelled as water. The model assumed boundary conditions of still air at 30°C surrounding the container. Three placements of coolant were modelled. The first was with all ice above the fish. The model was then tested with the ice

Figure 1. EQ container.

divided in half with one half on top of the "10-pound" boxes and one half in a layer between the second and third "10-pound" boxes from the bottom. The third ice placement had half the ice above the fish and half underneath it. This was done in order to try to determine the best of the three placements of the ice for the processor.

The model was then subjected to a boundary condition of still air and temperatures similar to those encountered in the flight to Los Angeles. Figure 2 shows these temperature fluctuations graphically.

The following is a list of the assumptions made in developing the finite element model of the EQ container.

1. The cardboard, the plastic liner and the insulation were treated as one material with the physical properties of beaded polystyrene.

2. The seafood in the polyethylene boxes had the same physical properties as was discussed in section 4.2.1.

3. The polyethylene boxes were not included in the model, but the seafood they would have contained had the same dimensions as the box.

4. The ice melted in bulk; that is, either it was all frozen water or liquid water.

5. Convection in the air spaces in the container occurred at a constant rate.

6. The boundary conditions consisted of still air and a distant temperature that was known.

7. The boundary conditions were the same on all sides of the box, including the bottom.

8. No radiation boundary conditions effected the box.

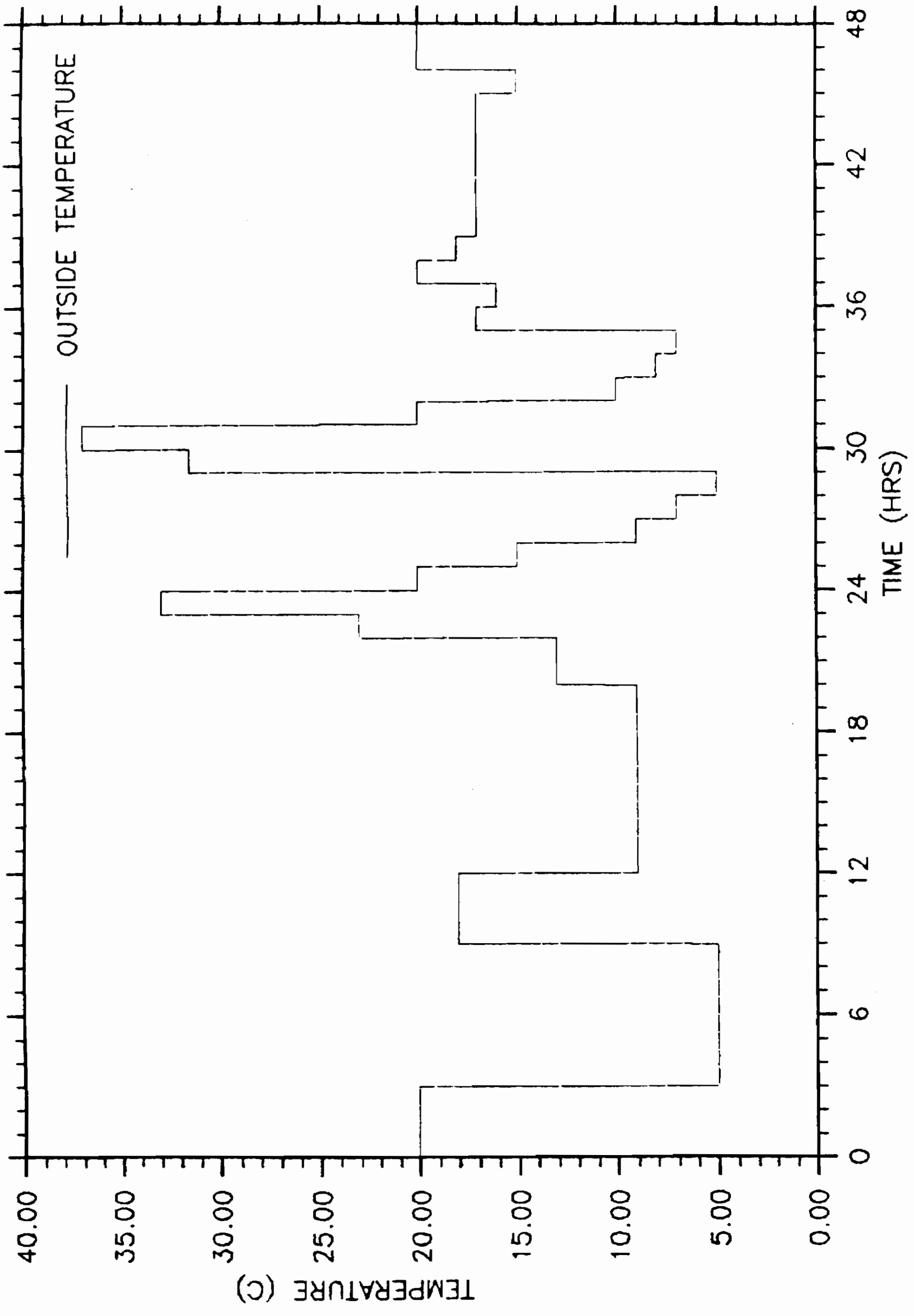

Figure 2. Boundary conditions applied to EQ model to simulate LA flight.

The first and third assumptions were made on the basis of the thickness of the materials: the liner and box wall were neglected. Since the cardboard would have been very difficult to model accurately as individual elements it was included as part of the insulation. In addition the physical properties of cardboard are within an order of magnitude of the properties of the insulation used. The thermal conductivity for cardboard is 0.064 $W/m{\cdot}^{\circ}C$ (ASHRAE, 1985). The thermal conductivity of polystyrene used was 0.040 $W/m{\cdot}^{\circ}C$ which is close that given in ASHRAE (1985). In addition, no density or specific heat were found for cardboard, but due to the large air spaces it was presumed they would be close to that of polystyrene which has a density of 16.0 kg/m^3 and a specific heat of 1210 $J/kg{\cdot}^{\circ}C$. Air has a specific heat of 1007 $J/kg{\cdot}^{\circ}C$ and density of 1.28 kg/m^3. The plastic liner and the polyethylene boxes were assumed to have little effect compared to the insulation due to their thinness and were neglected in the model. These assumptions would make the model more conservative as they would act as small insulators between the heat flowing into the box and the fish. Again it should be noted that the properties of polyethylene are close to those of the seafood. The third assumption was made to account for the shape of the "10-pound" boxes.

The fourth assumption was made to simplify the model. If each element of ice had been allowed to melt individually it would have been extremely difficult to model. The total heat flow into each of the ice elements was stored at each time step. The total heat flow into the volume of ice was then calculated. After each time step, an integration was performed using the trapezoidal method to determine the sum of heat flow into the ice. This value was compared to the total amount of energy needed to melt the ice. If it was less, then the ice remained frozen. If it was greater, then an interpolation was performed to estimate the time of melting and the model was rerun using water in the place of ice from that point. This assumption may also be conservative as it lowers the amount of time that the more central elements would need to melt.

Assumption five was made for convenience and because it would be difficult to know what these convection currents would look like and thus what the actual convective coefficients would be. The convective currents would also change as time increased and may even switch directions if the box is placed into a cool environment. Assumptions six and seven were made, because it was impossible to determine the actual boundary conditions of the boxes while in shipment. The bottom of the box, of course, should seldom encounter a convective boundary condition, however, the type of boundary condition it would encounter is impossible to tell as it would, upon coming into contact with any surface either heat or warm that surface so that a constant temperature boundary would also not exist for too long. Assumption nine would apply to all cases except if the box were placed near a very warm or very cold object or if it were placed into direct sunlight. Even if these conditions existed the box is white and has a wax coating which would reduce any radiation due to it's high reflectivity. Overall, the assumptions made should not adversely effect the overall performance of the model.

Chapter 5

Results and Discussion

5.1 "10-Pound" Box Cooling Experiments

Results of the experiments described in section 4.1 appear as Figure 3. The cooling time for a "10-pound" box of fish was 12 hours. Comparison with the finite element model, which is described below, shows that the constant temperature boundary condition was not maintained during the cooling of the "10-pound" box of fish. This is shown by the fact that the actual cooling time was much longer than that predicted by the model. The series of cooling tests, however, did yield similar cooling times which indicates that the actual time to cool a "10-pound" box of fish in ice will be 12 hours in practice.

Also conducted were cooling experiments on "20-pound" boxes and "10-pound" bags. These results appear in Appendix C. The experiments conducted on the "20-pound" box of fish and the "10-pound" bag of fish show a cooling time of approximately 18 hours for both containers.

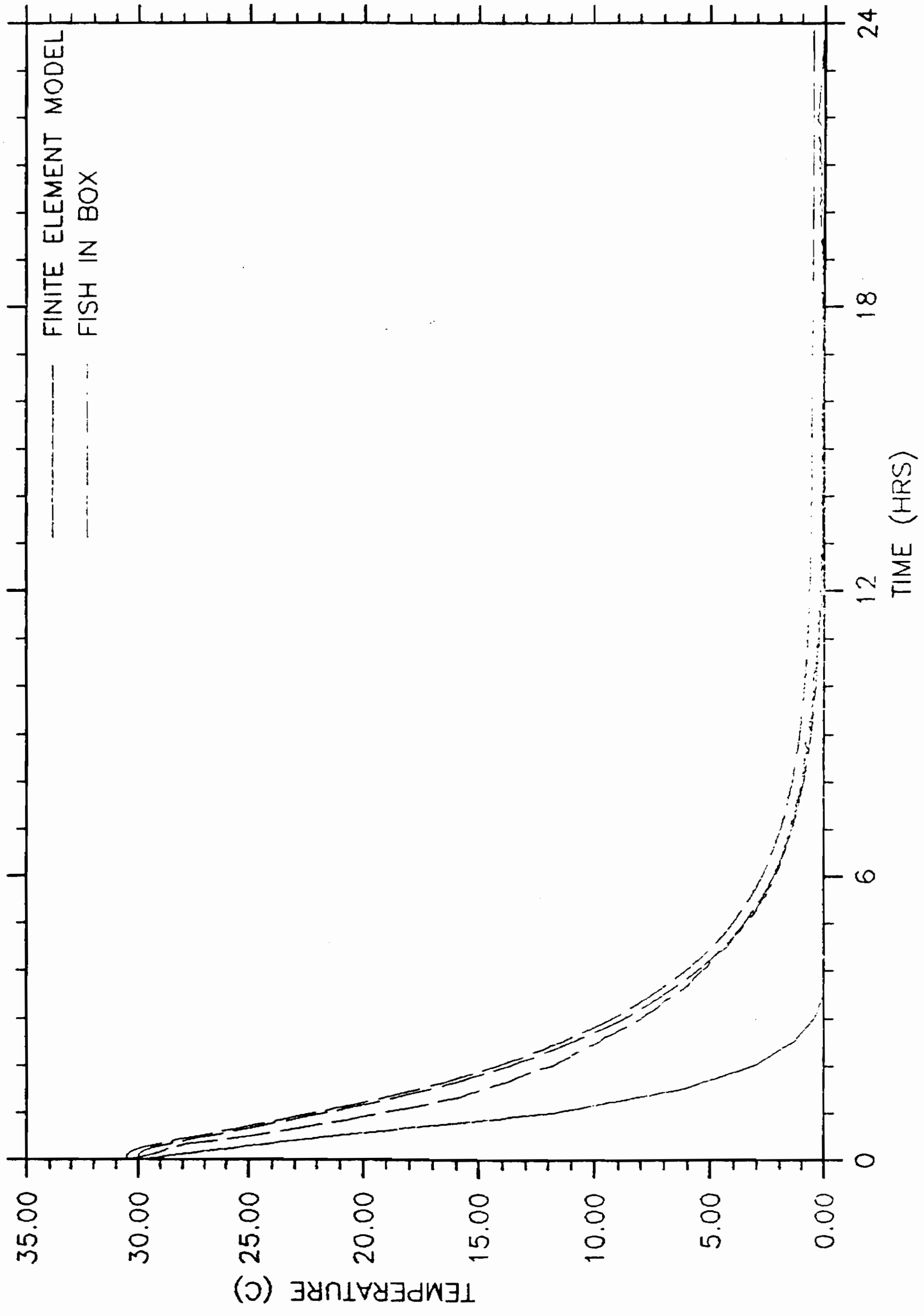

Figure 3. Experimental cooling tests for "10-pound" box of fish.

The "10-pound" bag experiment with the peculiar cooling curve may be the result of the thermocouple probe being dislodged as it was placed into the cooler. The thermocouple was reinserted into the bag, but probably was not placed back into the center of the mass of fish and remained near the outside of the bag.

5.2 Finite Element Analysis of the "10-Pound" Box

5.2.1 Physical Properties Experimentation

5.2.1.1 Density

The results of the specific gravity experiments are shown in Table 1:

Table 1. Specific gravity of two species of fish.

Fish ID No.	Species	Specific Gravity
1	Bluefish	1.071
2	Bluefish	1.077
3	Bluefish	1.078
4	Bluefish	1.076
5	Bluefish	1.074
6	Croaker	1.024
7	Croaker	1.032
8	Croaker	1.026
9	Croaker	1.044

The bluefish and croaker had average densities of 1075 and 1032 kg/m^3 , respectively.

These values correspond well with value of 1075 kg/m^3 mentioned in Wheaton and Lawson(1985). The value of 1075.0 kg/m^3 was used in the modeling of the "10-pound" fish container and the EQ container.

5.2.1.2 *Thermal Conductivity*

Table 2 shows these average thermal conductivities for the samples of the fish tested over the whole range of temperature. The variation over the temperature range of 0 to 30°C was small and therefore neglected in modeling.

Table 2. Thermal conductivity of six species of fish.

Fish ID No.	Species	Thermal Conductivity $W/m\cdot{}^{\circ}C)$
1	Bluefish	0.473
2	Flounder	0.485
3	Whiting	0.491
4	Spot	0.393
5	Sea trout	0.464
6	Mullet	0.415

These values compare favorably with the values found in the literature. For modeling an average value of 0.45 $W/m\cdot{}^{\circ}C$ was used to estimate the thermal conductivity of the boxed fish.

5.2.2 Results of the Finite Element Model

The physical properties for the fish and polyethylene used in this investigation are shown below in Table 3.

Table 3. Thermal properties for fish and polyethylene box.

Material	Density *kg/m³*	Specific Heat *J/kg*	Thermal Conductivity *W/m·°C*
Polyethylene Box	915	2300	0.32
Fish	1075	3536	0.45

The effective thermal properties were estimated on a volumetric basis as was described in 4.2.1.4. The results are contained in Table 4.

Table 4. Thermal properties for fish-air and gel-air combinations.

Material	Density *kg/m³*	Specific Heat *J/kg*	Thermal Conductivity *W/m·°C*
Fish/Air	649	2648	0.30
Gel/Air	850	3710	0.488

The results for the "10-pound" box cooling as modeled by ANSYS were shown in Figure 3 along with the experimental results.

Figure 4 contains the results for the cellulose gum/water cooling experiments, which were performed to investigate the discrepancy between the model and fish cooling curves in Figure 3. The figure reveals that it is possible to maintain a constant temperature boundary condition of "10-pound" box, if the cooler in which it is placed can be shaken often. The model using the properties in Table 4 appears to provide a reasonable representation of the actual heat transfer. It is not likely that a shipper would take the time to agitate boxes if they were cooled with ice therefore, the 12 hour cooling time estimate for a "10-pound" box of fish and the 18 hour cooling time estimate for both the "20-pound" box and "10-pound" bag are the most realistic.

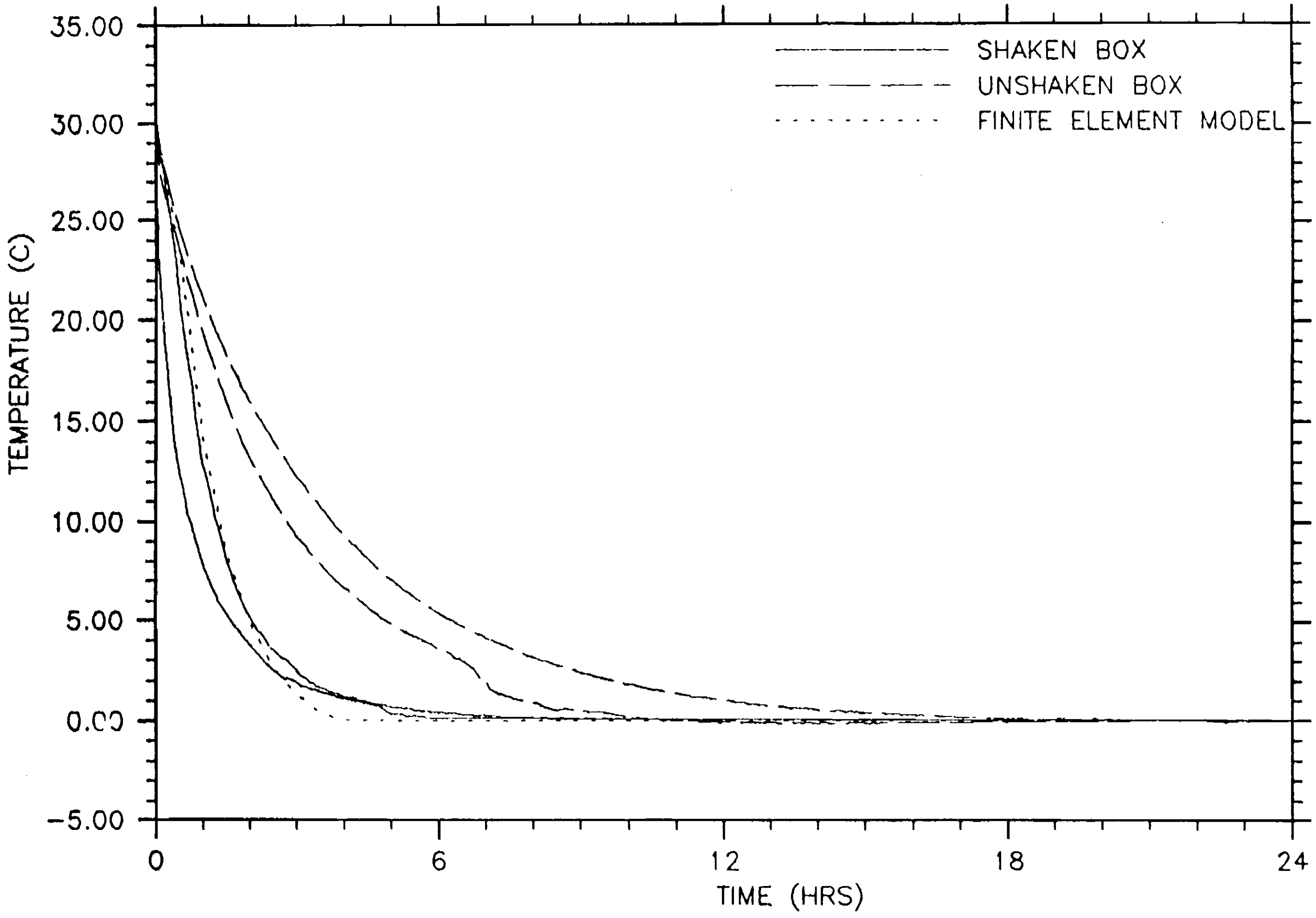

Figure 4. Experimental cooling tests for "10-pound" box of gel.

The model was also used to simulate cooling a box using a refrigerator at different air speeds. Figures 5 and 6 show the model run for boundary conditions in a refrigerator with an interior temperatures of 1.67°C and 0°C, respectively. The model shows that in refrigerators that have high air speeds cooling of the fish in the "10-pound" box may occur almost as quickly as that in a cooler packed with ice being shaken to insure the constant temperature boundary condition. For a refrigerator with no forced air movement it would take approximately 24 hours to cool fish at 30°C to an adequate temperature for shipment. The model also predicts very quick cooling, approximately 4 hours, for a constant temperature boundary condition.

5.3 Gel Pack Heat Absorption Experiments

The results for the gel packs tested at Texas A and M University are shown in Table 5. The results show that ice has a larger enthalpy than any of the gel substances tested. This means that ice has the ability to absorb more energy than any of the gels that were tested. The reason Insul Ice and Uotek have two values for enthalpy was that there were two melting points for these gel packs.

These results also indicate that the gel substances tested consisted mostly of water. The pack with the highest water content, the Kool-It pack, also had the highest enthalpy, while the gel pack with the lowest moisture content, the Magic Ice pack, had the lowest enthalpy.

The gel packs and the ice in ziploc bags gave similar curves as for the warming in the cooler as shown in Figure 7. This seems to indicate that both ice and the substance used in the gel packs (Kool-It) tested have similar warming properties and that neither would necessarily be an advantage over the other based solely on warming characteristics. In actual air shipments,

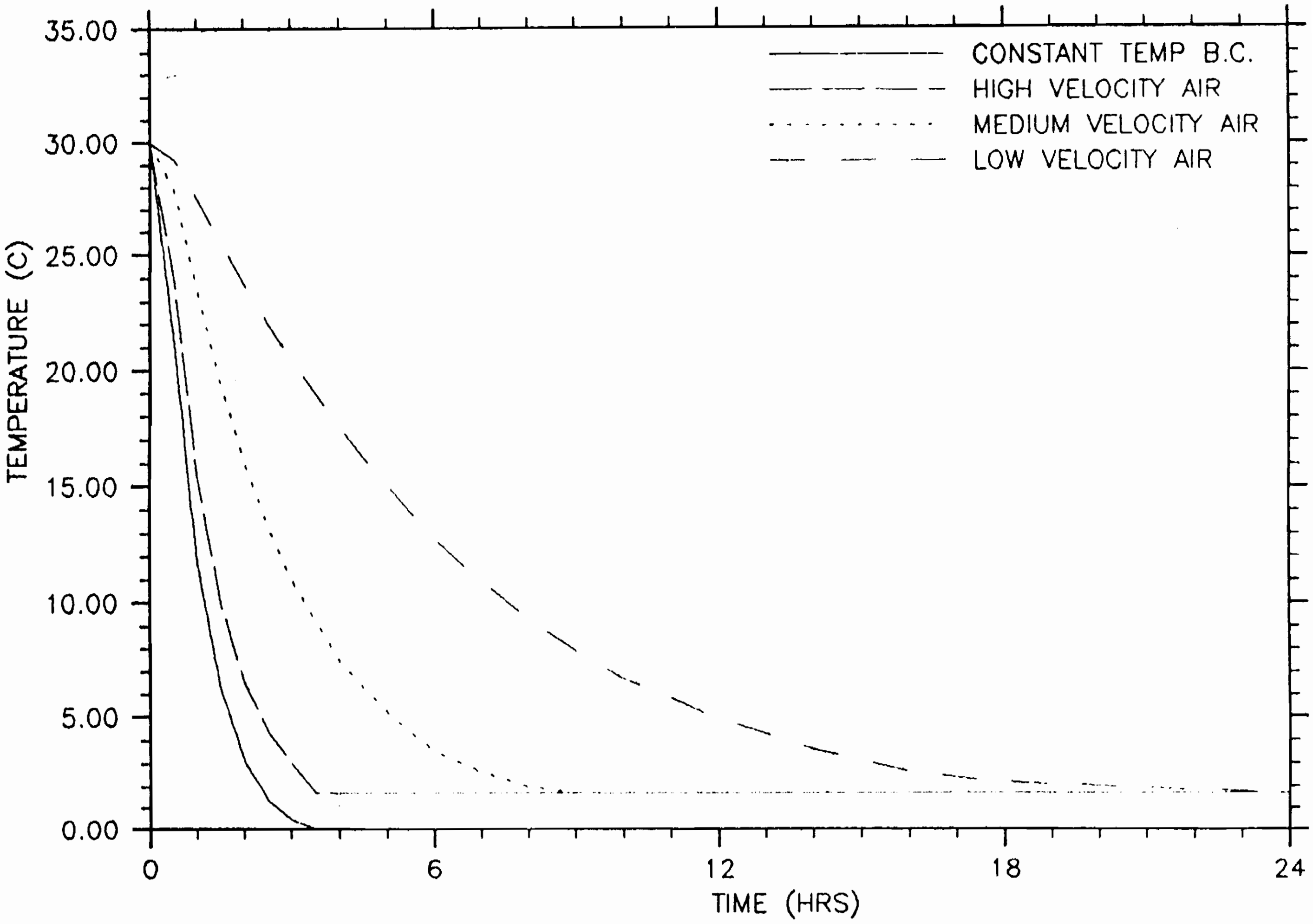

Figure 5. Model results for "10-pound" box with convection boundary (1.67°C)

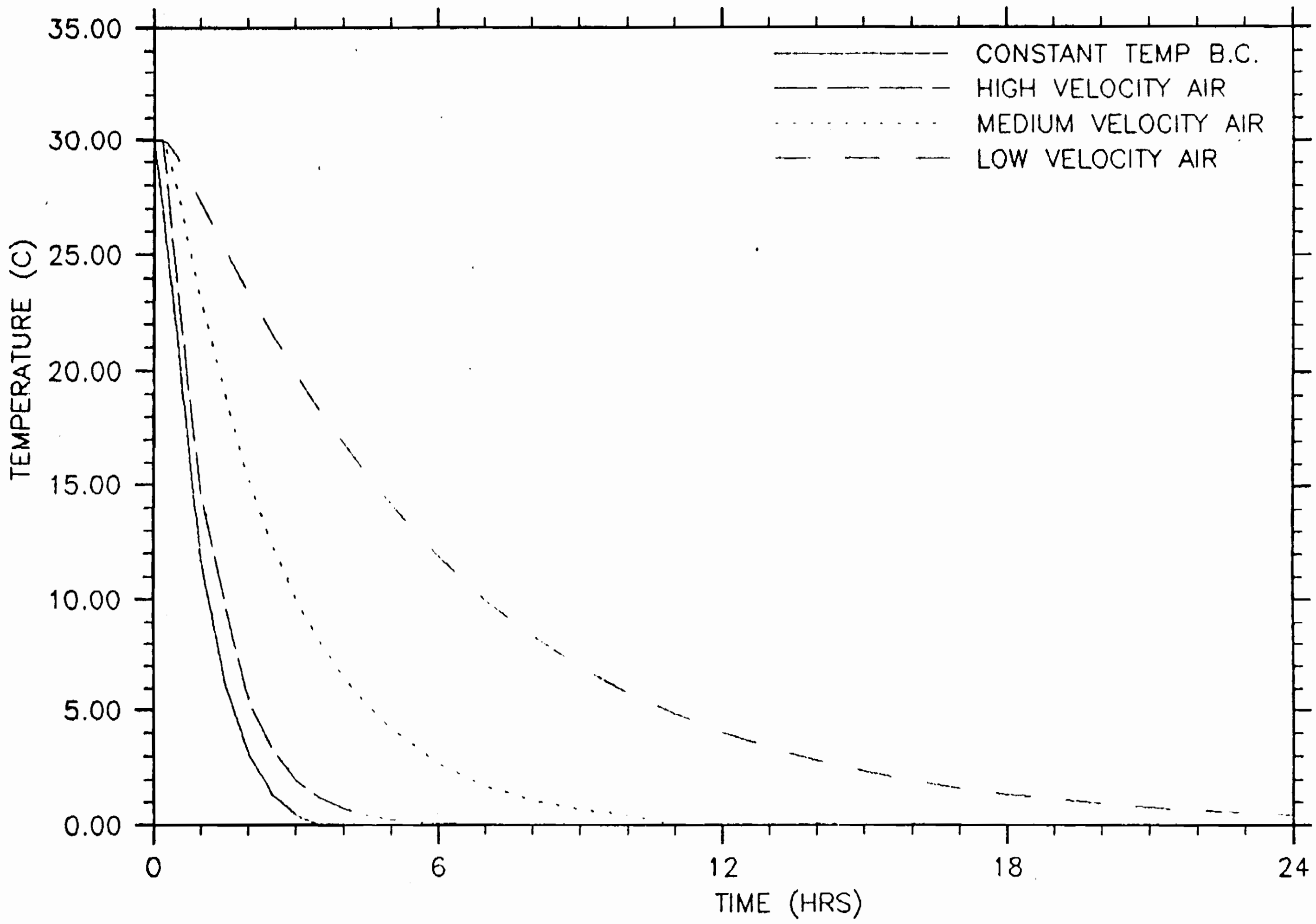

Figure 6. Model results for "10-pound" box with convection boundary (0°C).

the coolant that can absorb the most energy would be the most desirable since it will be absorbing or "intercepting" the heat that enters the shipping container.

Table 5. Properties of substance inside various gel packs.

Material	**Enthalpy** *cal/gm*	**Moisture Content** %
Tech Pack	64.4	97.6
Kool-It	79.2	99.9
Arctic Pack	71.2	98.2
Blue Ice	57.4	94.5
Super Ice	67.3	96.7
Insul Ice	2.0 64.9	98.9
Uotek	29.8 6.0	74.6
Magic Ice	24.2	72.3
Water	80.6	100.0

5.4 Air Transportation Temperature Measurements

The most relevant data for modeling purposes were the outside temperatures, which are shown in Figures 8 and 9. Figure 8 shows the outside temperature for a flight to Los Angeles and back. Figure 9 is for a flight to and from Phoenix. Both figure show a total time of 72 hours which was the total time from packing the box until they were received at the airport and data was retrieved from the data logger.

These two figures reveal some interesting occurrences. For example in the flight to Los Angeles the temperature dropped as low as 3°C. This probably occurred in a refrigerated storage area between flights. The temperature in the cargo area of an airplane is usually maintained at approximately 7°C (45°F) (Loughran, 1987). This is also encouraging, because

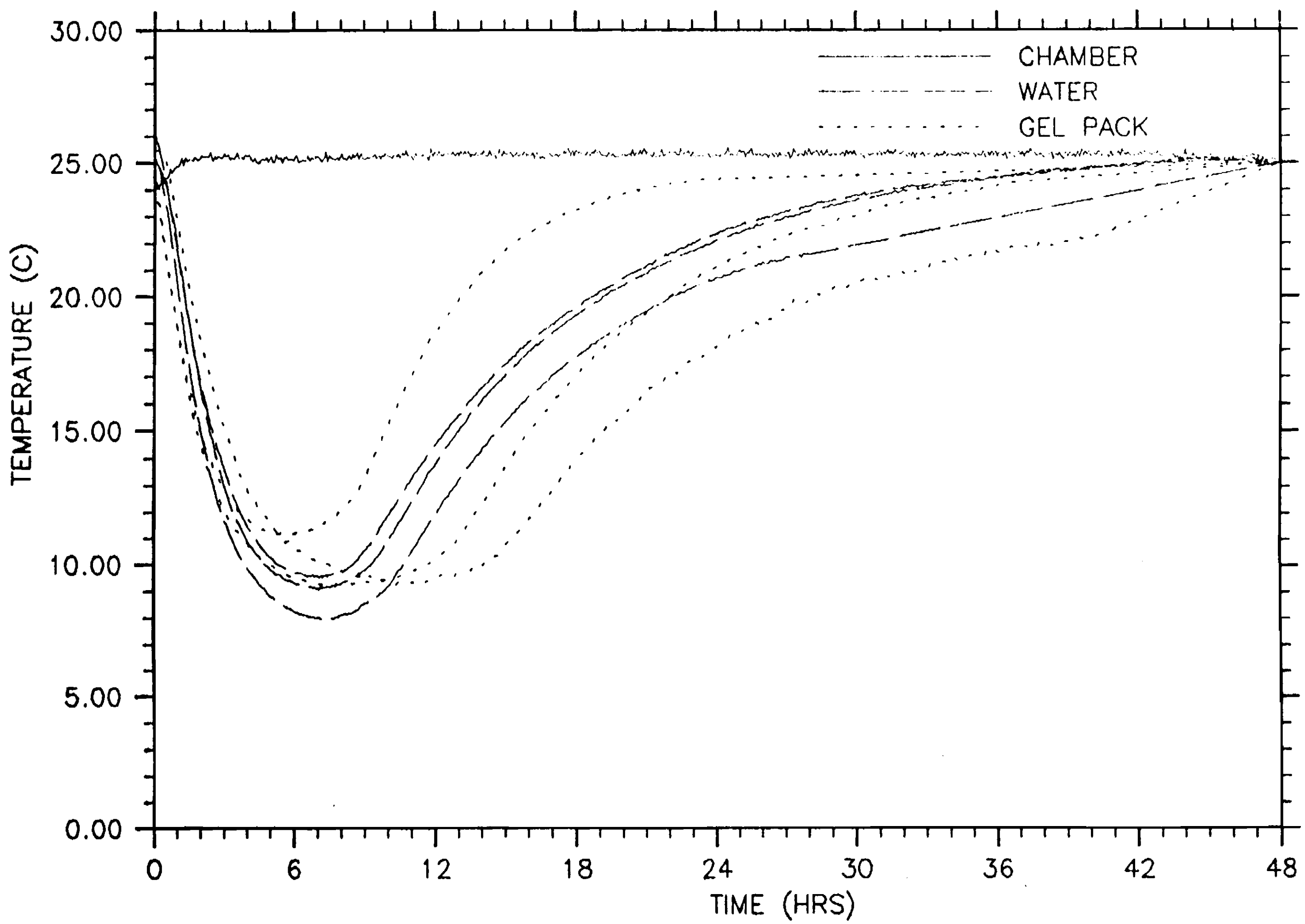

Figure 7. Warming curves for gel pack and ice.

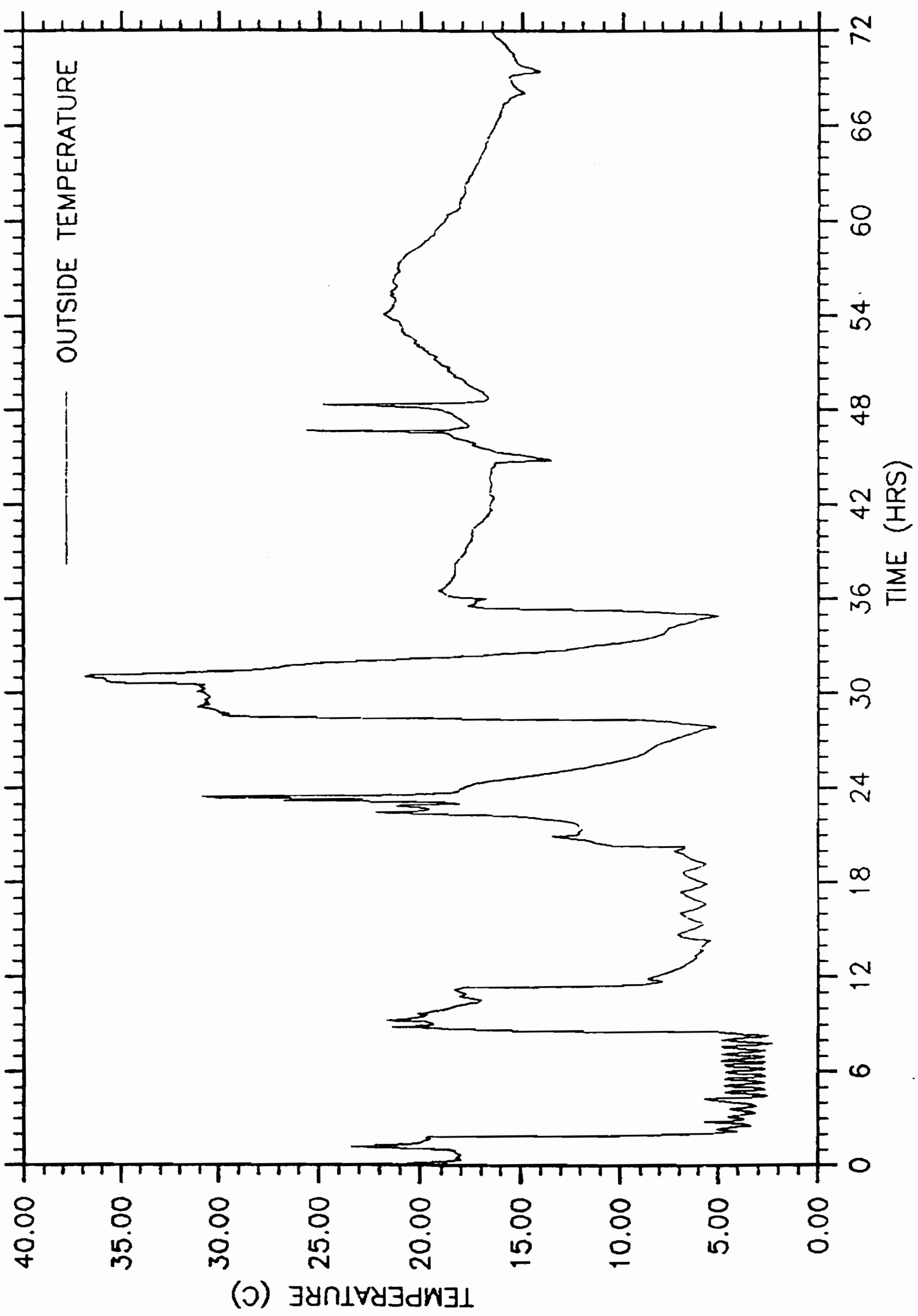

Figure 8. Outside package temperatures for flight to Los Angeles.

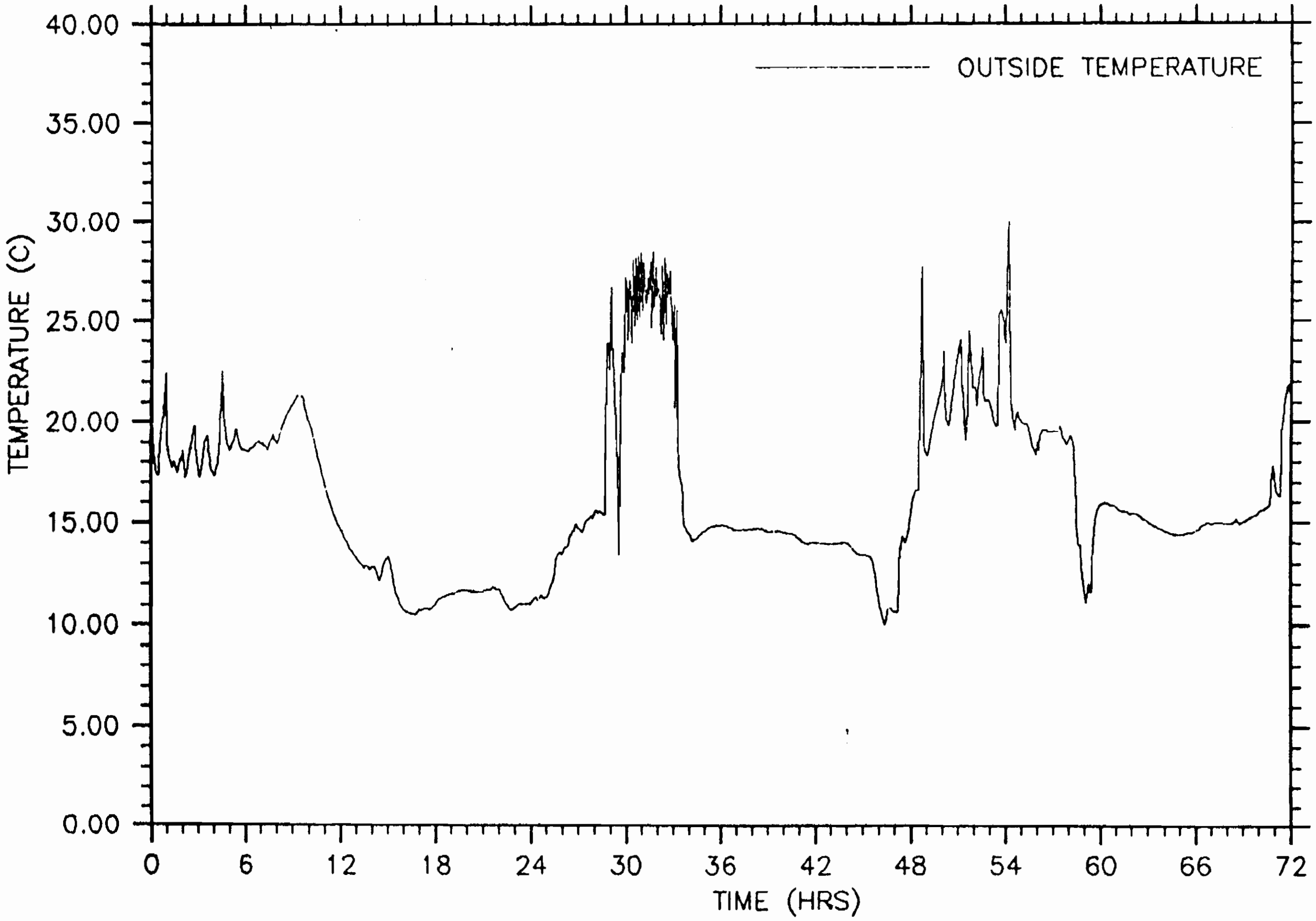

Figure 9. Outside package temperatures for flight to Phoenix.

the lower air temperature will cause less heat loss from the box. However, the carton also experienced temperatures higher than expected. Again in Figure 9 it can be seen that the temperature went above 35°C (95°F). This temperature and all the other peak temperature did not last very long on the flight to Los Angeles. However, on the Phoenix flight, a temperature around 30°C lasted for close to six hours. It can only be speculated that the box must have been left in a loading dock in the sun during that time or some other strange occurrence must have taken place. Overall, the results reveal the expected conclusion that the containers being shipped by air will encounter extreme temperatures (above 30°C and below 5°C) at some times during the shipment, but in general the temperature can be expected to be between 10 and 25°C.

Two other temperatures were plotted for comparison with the finite element model. These were the center temperature of the fish and the temperature of the center of the insulation inside the box. These results appear in Appendix D. The temperatures for these two positions over time are plotted along with the temperatures the model calculated. It is difficult to compare these as equal volumes of ice were not used for the model and the experiments, and in the model it was assumed that the fish would be boxed in "10-pound" boxes and in the experiments the fish were placed in the EQ container in bulk. The comparison does indicate that the model provides a reasonable representation of the containers heat transfer response.

5.5 Finite Element Model of the EQ Shipping Container

The results of the modelling of the EQ container are shown in Table 6 and Figures 10 through 27. In this table and the figures *Icing method 1* refers to all the ice placed on top of the seafood. *Icing method 2* refers to the case where the ice is split between the top of the fish and the second and third "10-pound" boxes from the bottom of the container. *Icing method 3* refers to the case where the ice is placed on top of the fish and on the bottom of the fish. *Constant BC* indicates the model run with the constant boundary conditions of still air at 30°C and *LA Flight* is used for the model with boundary conditions shown previously in Figure 2 and which were intended to be similar to those encountered during the flight to Los Angeles.

Table 6. Ice melting time for EQ models.

Model Type	Icing Method	Ice Position	Melting Time *hours*
Constant BC	1	Top	8.15
Constant BC	2	Top	4.78
		Middle	7.24
Constant BC	3	Top	4.78
		Bottom	4.75
LA Flight	1	Top	21.2
LA Flight	2	Top	13.4
		Middle	15.6
LA Flight	3	Top	11.7
		Bottom	12.6

Table 6 shows that the ice could be expected to melt in less than 8.15 hours in all cases if the EQ container were to encounter a continuous boundary condition of 30°C and still air. A more realistic case would be for a shipment to encounter fluctuating temperature boundary conditions modelled in the LA flight model. In this case, the ice would be expected to melt much slower, taking as long as 21.2 hours in the case where all of the ice is on top of the product. However, the best icing method should not be assumed to be the icing method where the ice lasts the longest, but where the temperatures in the product remains the lowest at all locations for the longest period of time.

For the icing method 3 with the constant boundary conditions the ice on the top of the product took a longer time to melt than the ice on the bottom. However, for LA flight model the ice below the product melted slower. The reason for this is that for the first 3 hours the box is exposed to an outside temperature of 20°C and then for 8 hours experiences only 5°C. Thus, during the first 3 hours the package warms due to this boundary condition and the during the next 8 hours cools and heat absorbed by the ice is reduced. The ice below was more closely exposed to this cooler environment and lost less energy as a result, and thus melted slower.

For Figures 10 through 27, each shows two cross-sections of an EQ container at the same time. The plot on the left corresponds to a cross-section at the edge of the fish which is exposed to the airspace between the fish and the insulation at the end of the container. The plot on the right shows the cross-section in the center of the container. The plots are shown at 6, 24 and 48 hours. Plots at times 12, 18, 30, 36 and 42 hours are shown in Appendix E. Figures 10 through 18 are for the models with the 30°C constant boundary condition. Figures 10 through 12 show this data for the container with the icing method 1. Figures 13 through 15 are for icing method 2. Figures 16 through 18 are for icing method 3. Figures 19 through 27 show the container cross-sections for the LA flight conditions. Figures 19 through 21 are for icing method 1. Figures 22 through 24 are for icing method 2. Figures 25 through 27 are for icing method 3. In all of these plots the location of the seafood is indicated by heavy lines inside of the container.

In terms of quality of the fish, the temperature should be maintained below 7°C for as long as possible (Martin and Flick, 1990). A temperature of 5°C is preferable and will be used in this discussion as a critical temperature. Looking at the plots for the constant boundary condition models, these plots reveal that the temperature exceeds 5°C somewhere in the mass of fish as early 6 hours in all cases except for the center cross-section with icing method 3.

The temperature exceeded 5°C for the model run with the boundary conditions of the Los Angeles flight much slower. For the model with icing methods 1 and 2 it took 18 hours before portions of the seafood reached this temperature although at 12 hours small sections had reached 5°C. These isotherms appear as Figures 55, 60 and 65 in Appendix E. The model with the icing method 3 did not reach the 5°C temperature until 24 hours. It appears that, although the ice melts faster when split between the top and the bottom of the fish, it is most effective in this arrangement. Overall, these plots show that for the boundary conditions of the Los Angeles flight, the shipments would be in poor condition if they arrived any later than 24 hours after the shipment began. It is also interesting to note that after 48 hours the temperature profiles for all the shipments are very similar. This is because after the ice melts the containers tend to equilibrate. After some point in time the effect of the coolant no longer matters. This is not to say that the placement of coolant is immaterial to shipment quality, just that after extreme spoilage placement of coolant becomes unimportant.

Looking at Figures 10 through 18, in particular Figures 10, 13, and 16, it is noticed that many isotherms reside near the edge of the EQ container. This is an indication of rapid change in temperature versus distance. That means that the insulation and the air space in this area is very effective in reducing heat transfer into the container.

More ice than was used in this modelling would be needed to maintain the temperatures of all the fish below 5°C for a total time of 48 hours for both sets of boundary conditions.

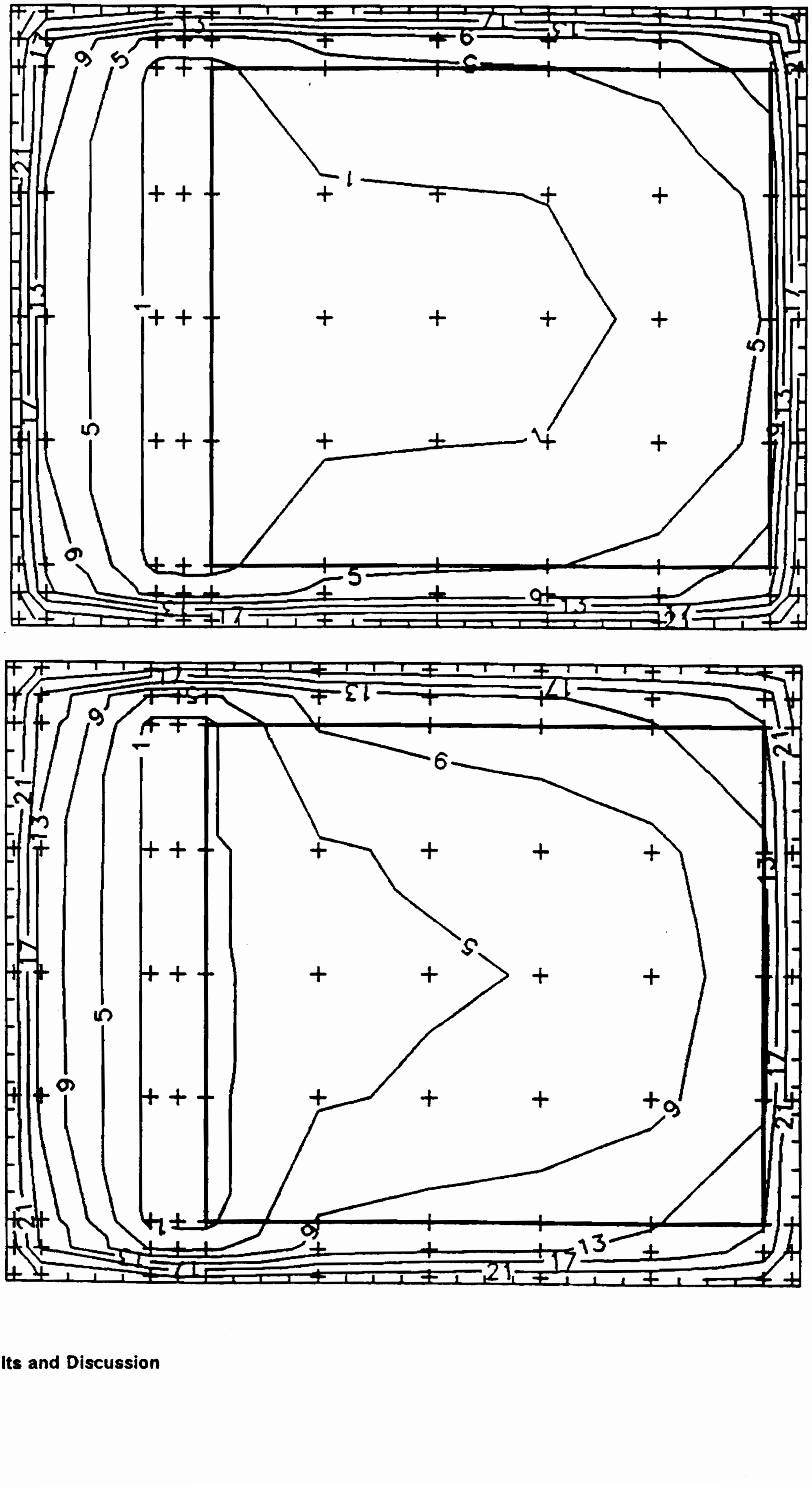

Figure 10. EQ container model at 6 hours with constant boundary conditions icing method 1.

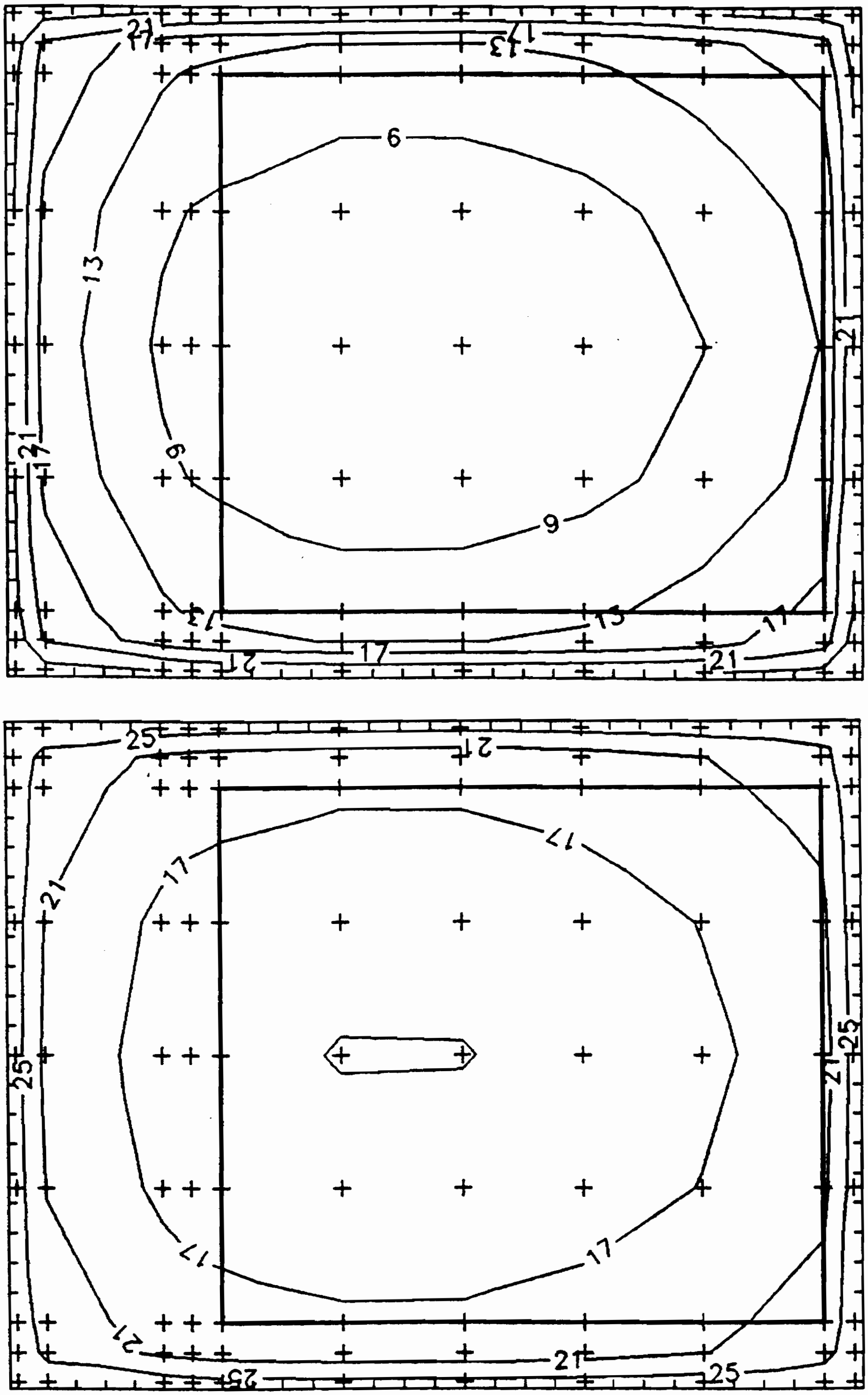

Figure 11. EQ container model at 24 hours with constant boundary conditions icing method 1.

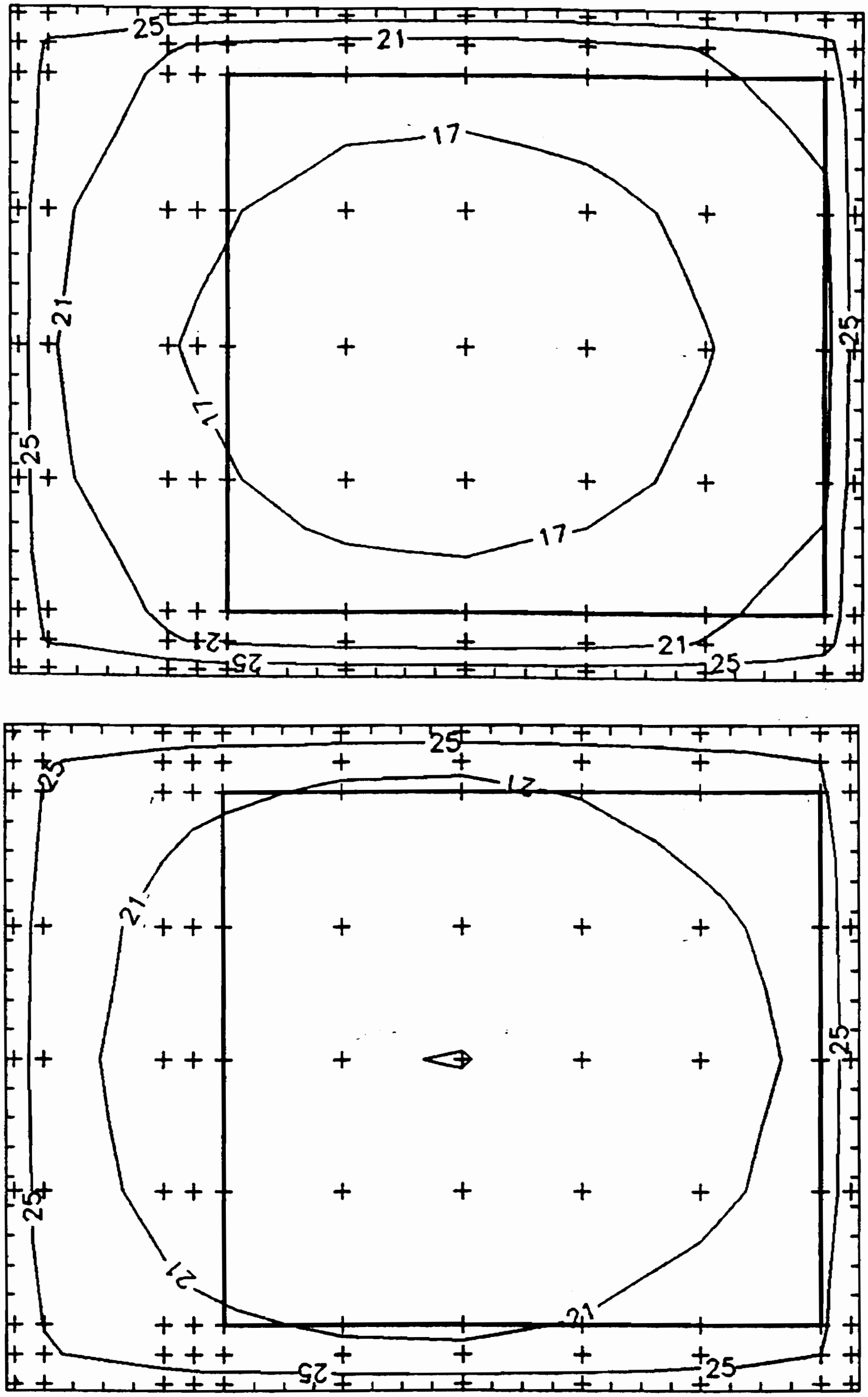

Figure 12. EQ container model at 48 hours with constant boundary conditions icing method 1.

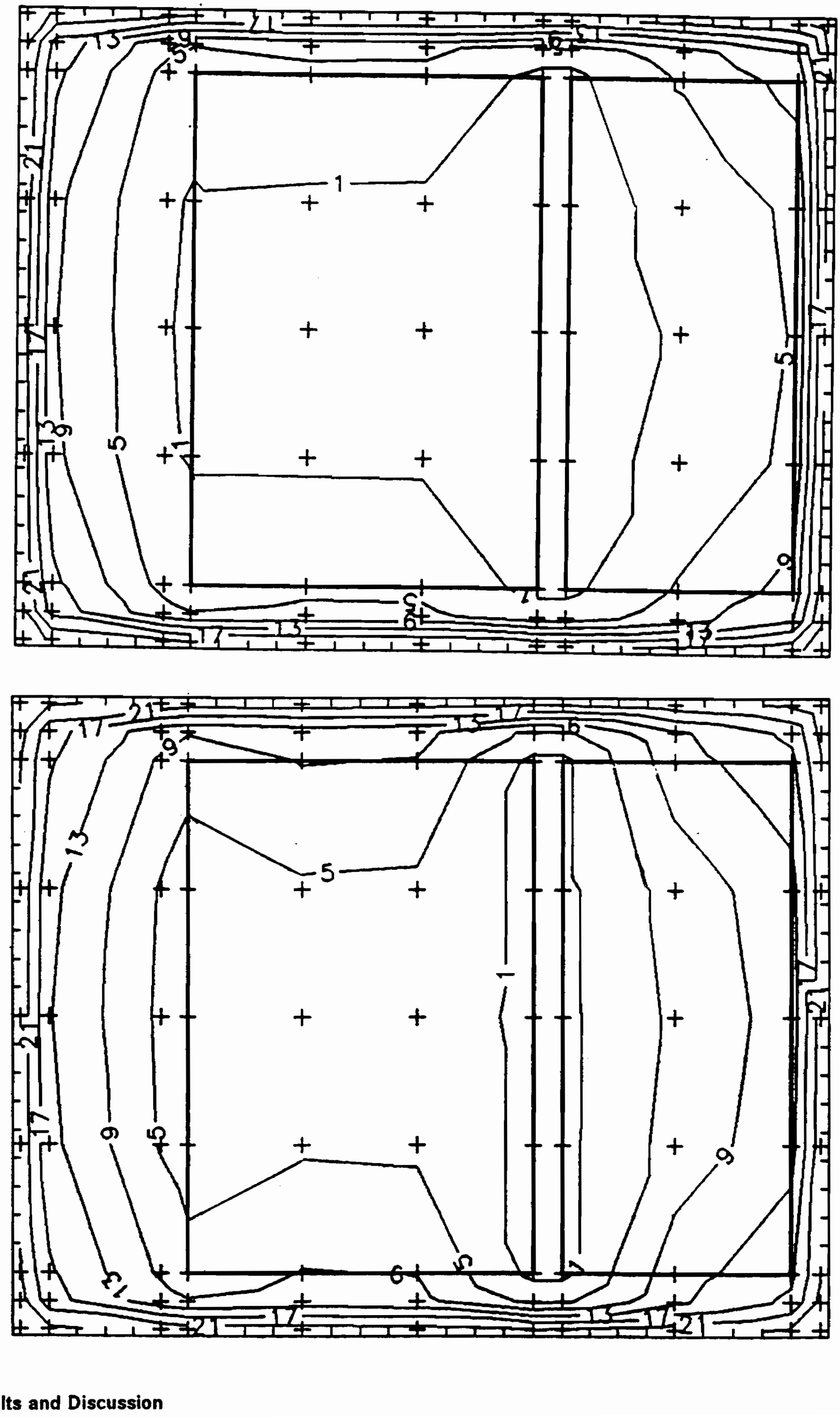

Figure 13. EQ container model at 6 hours with constant boundary conditions icing method 2.

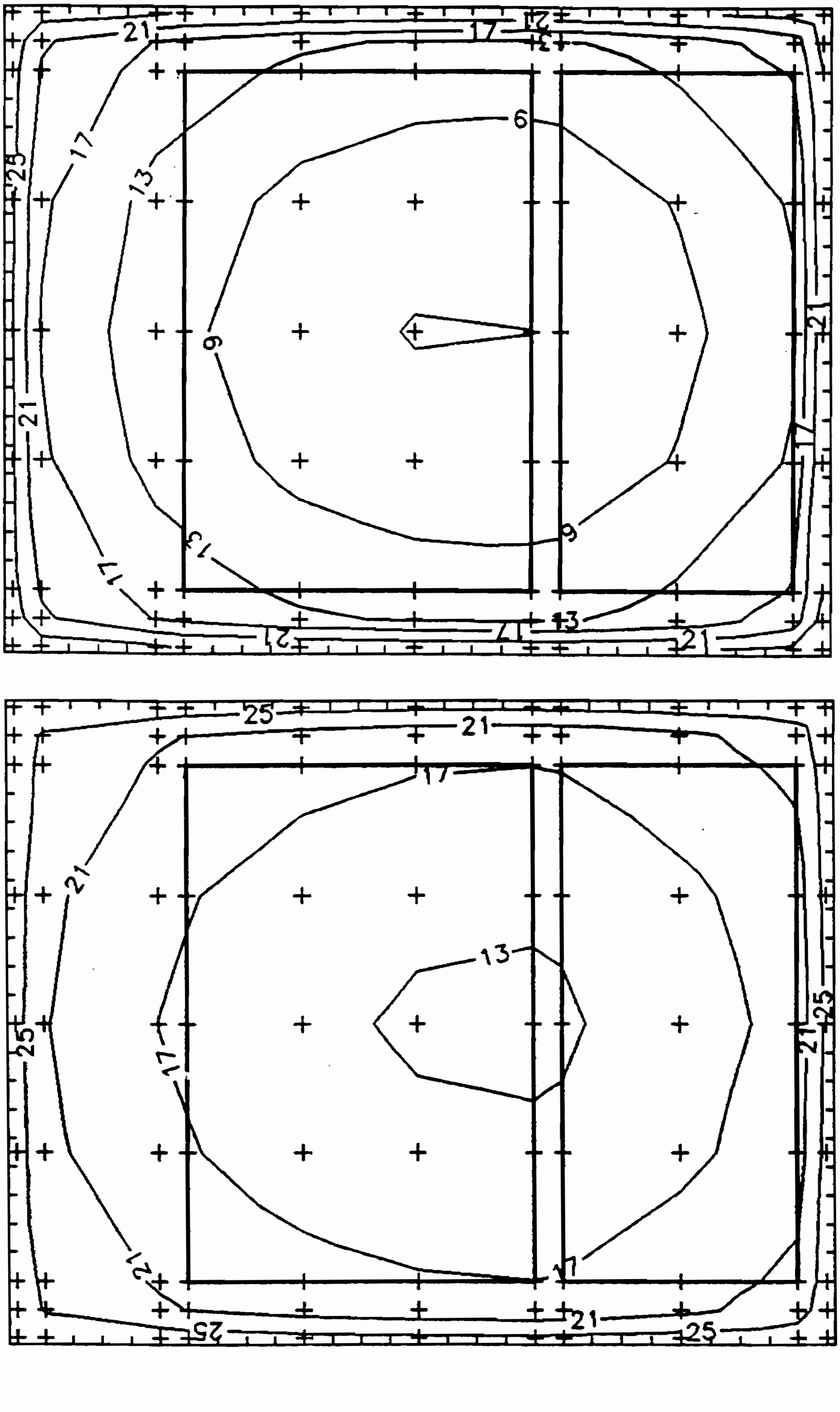

Figure 14. EQ container model at 24 hours with constant boundary conditions icing method 2.

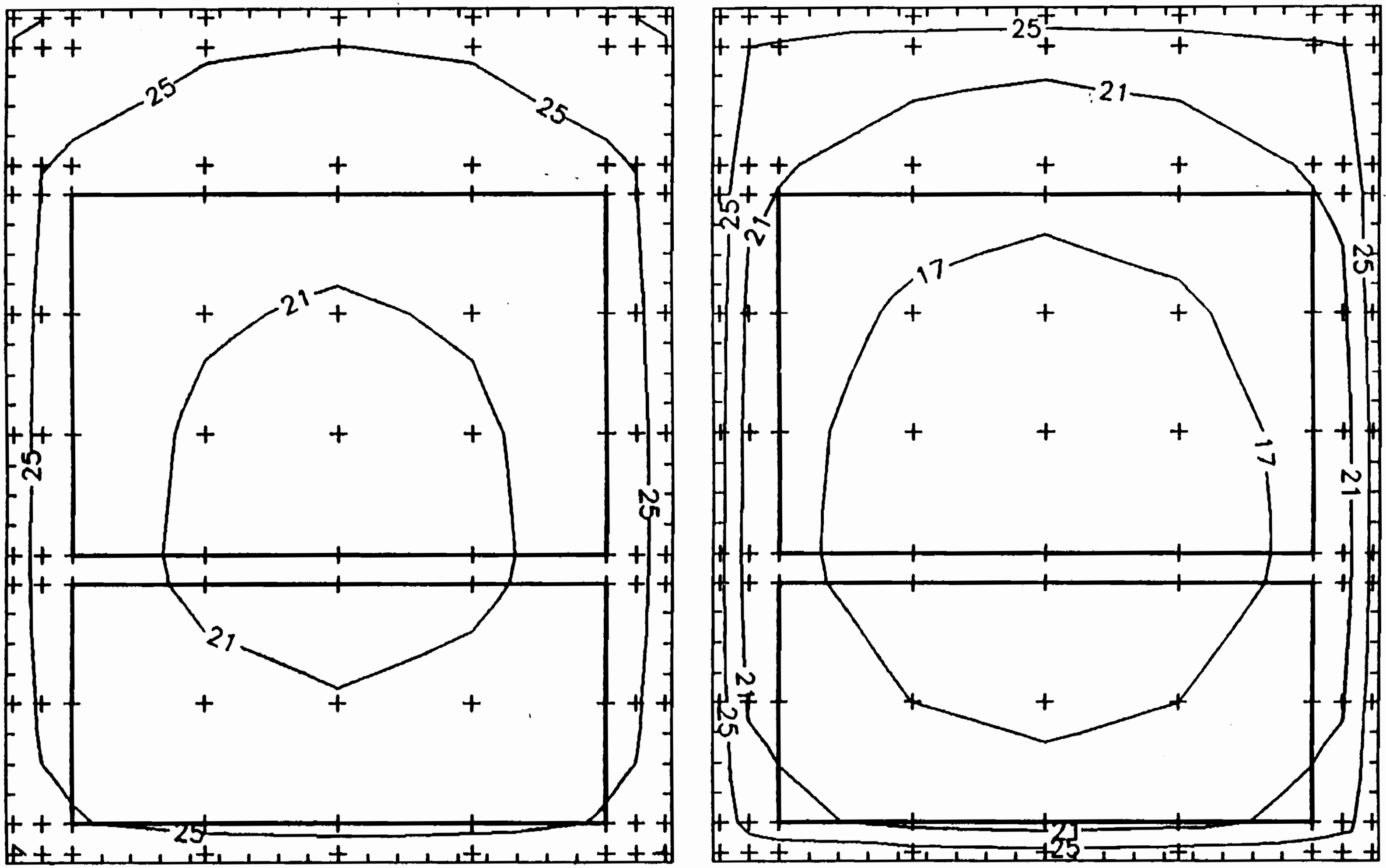

Figure 15. EQ container model at 48 hours with constant boundary conditions icing method 2.

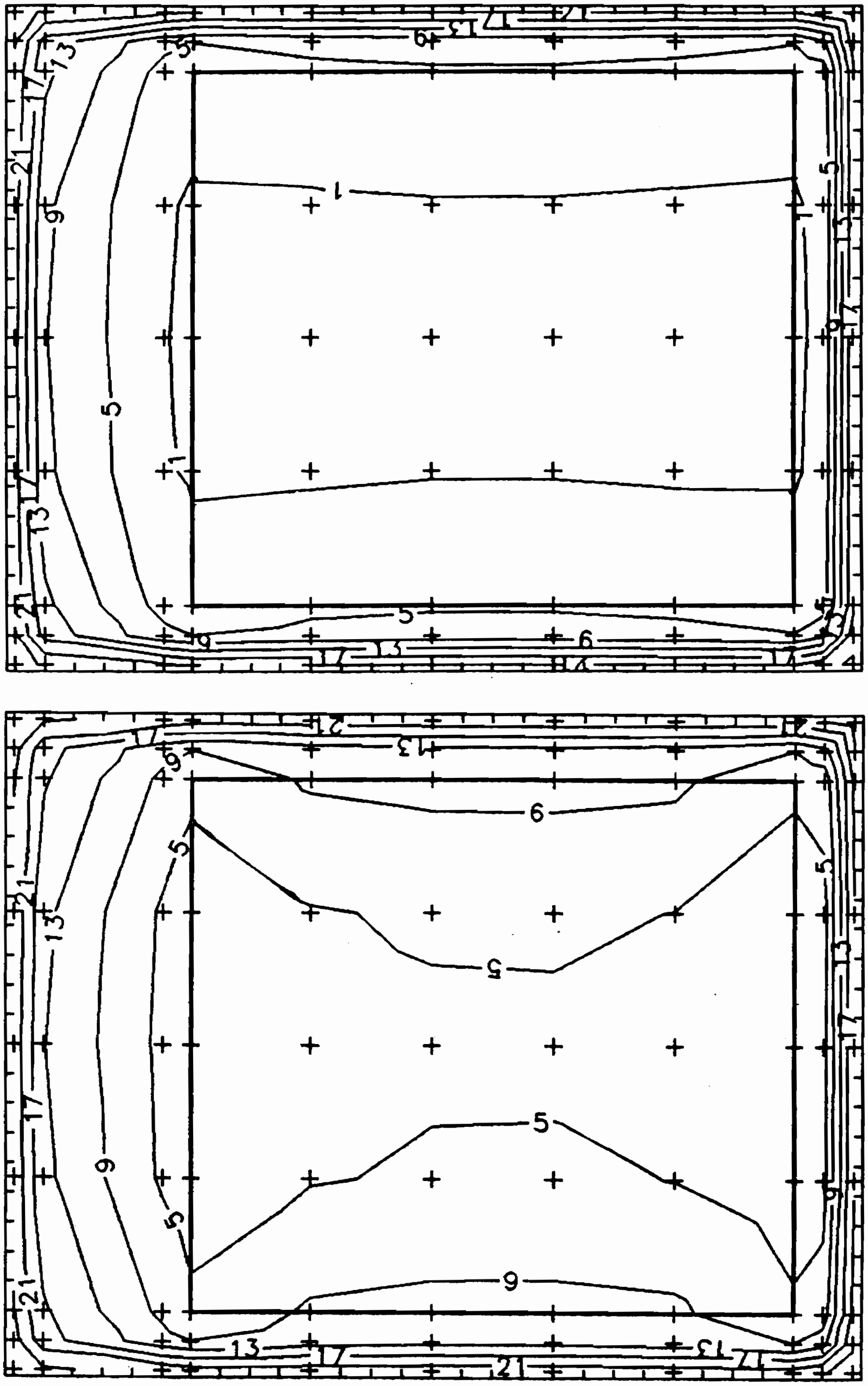

Figure 16. EQ container model at 6 hours with constant boundary conditions icing method 3.

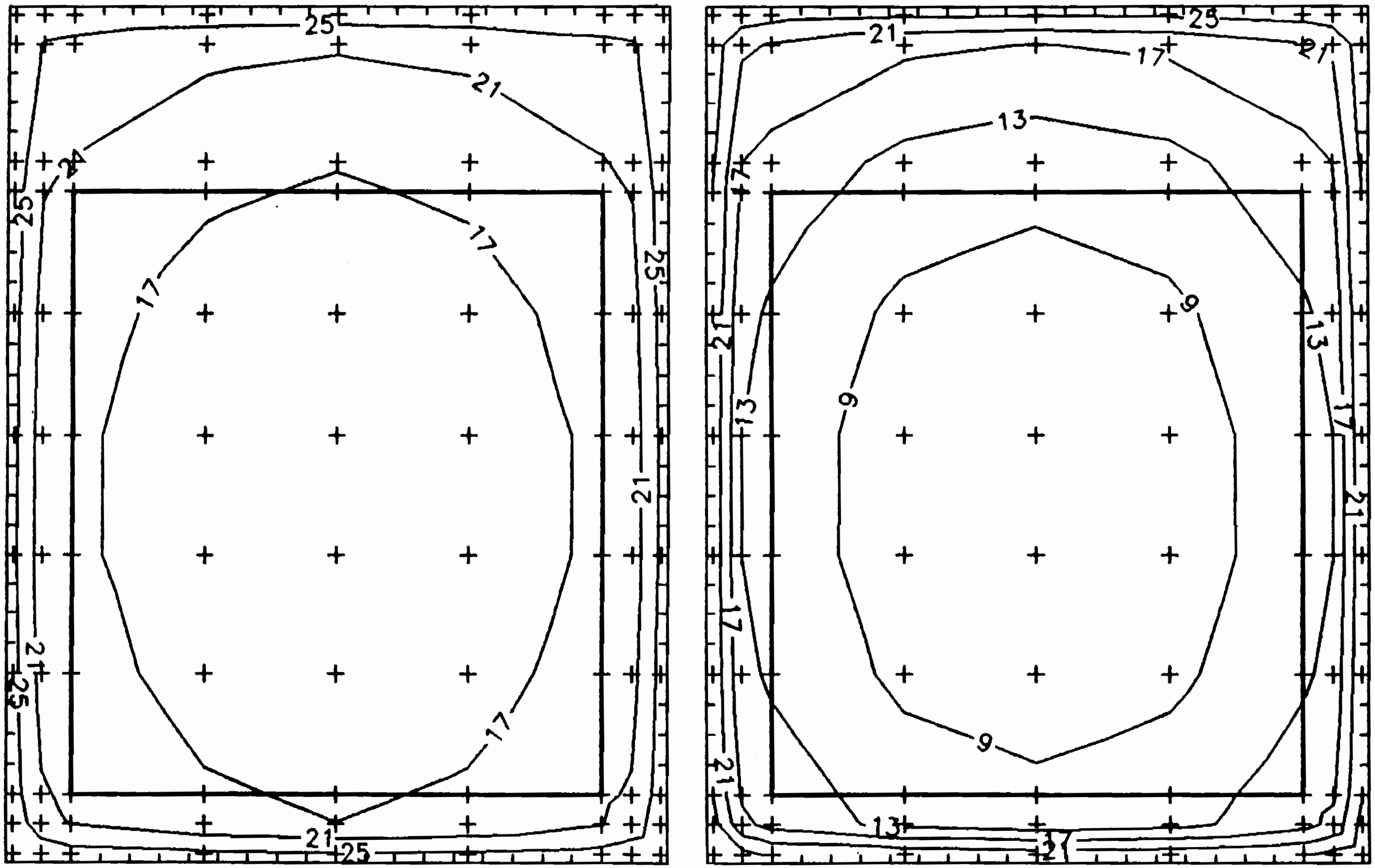

Figure 17. EQ container model at 24 hours with constant boundary conditions icing method 3.

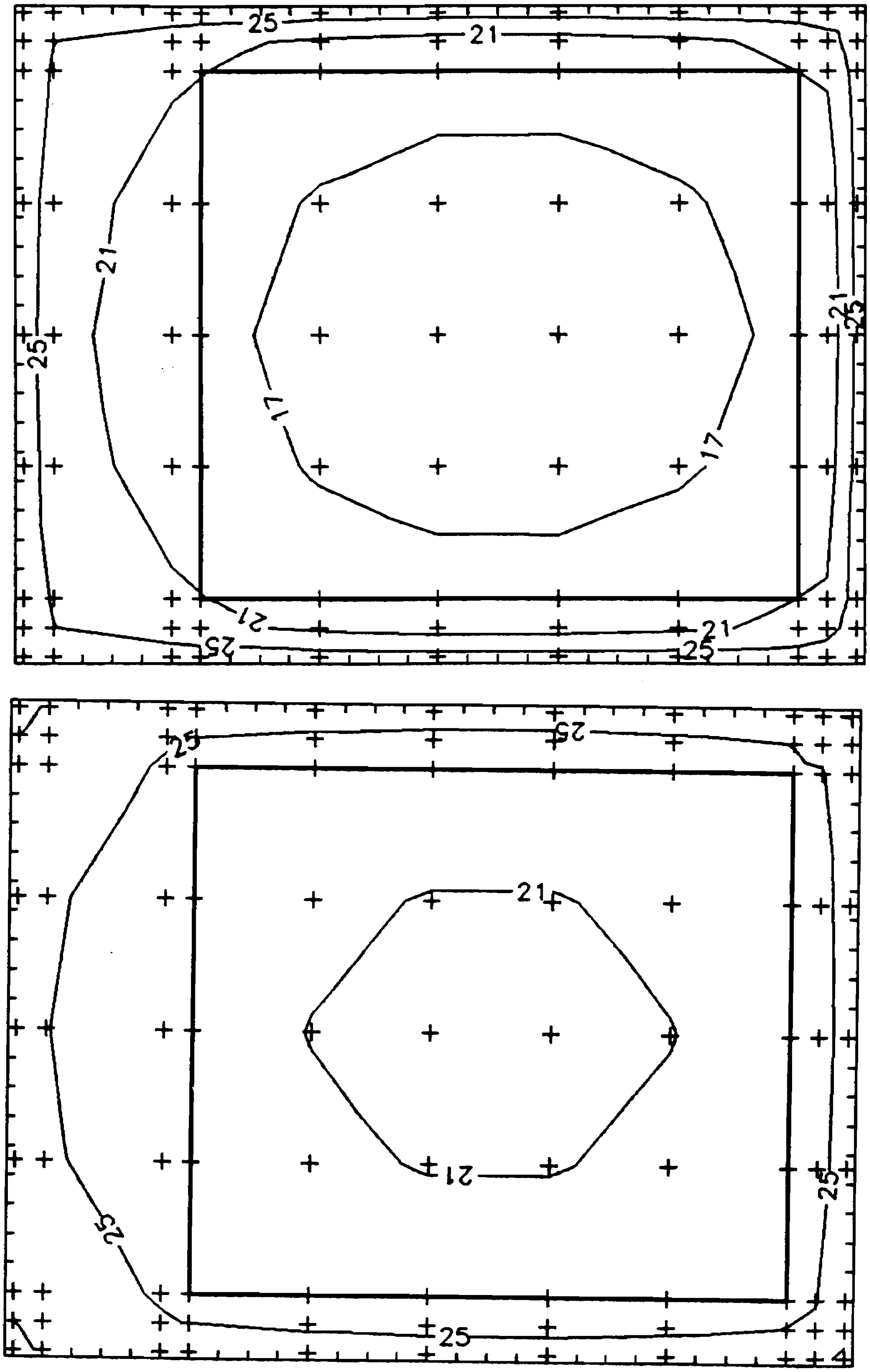

Figure 18. EQ container models at 48 hours with constant boundary conditions icing method 3.

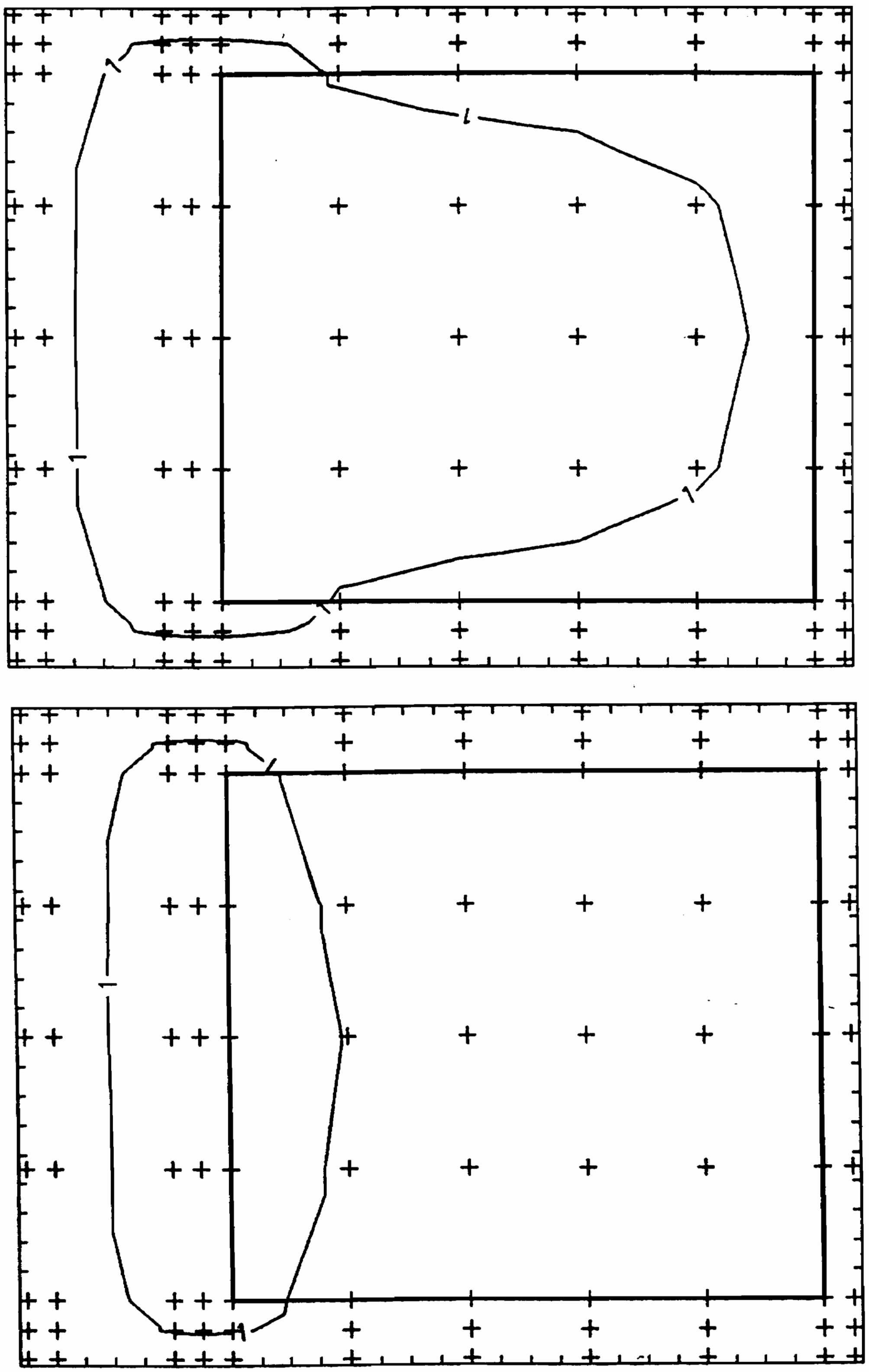

Figure 19. EQ container model at 6 hours for LA flight; icing method 1.

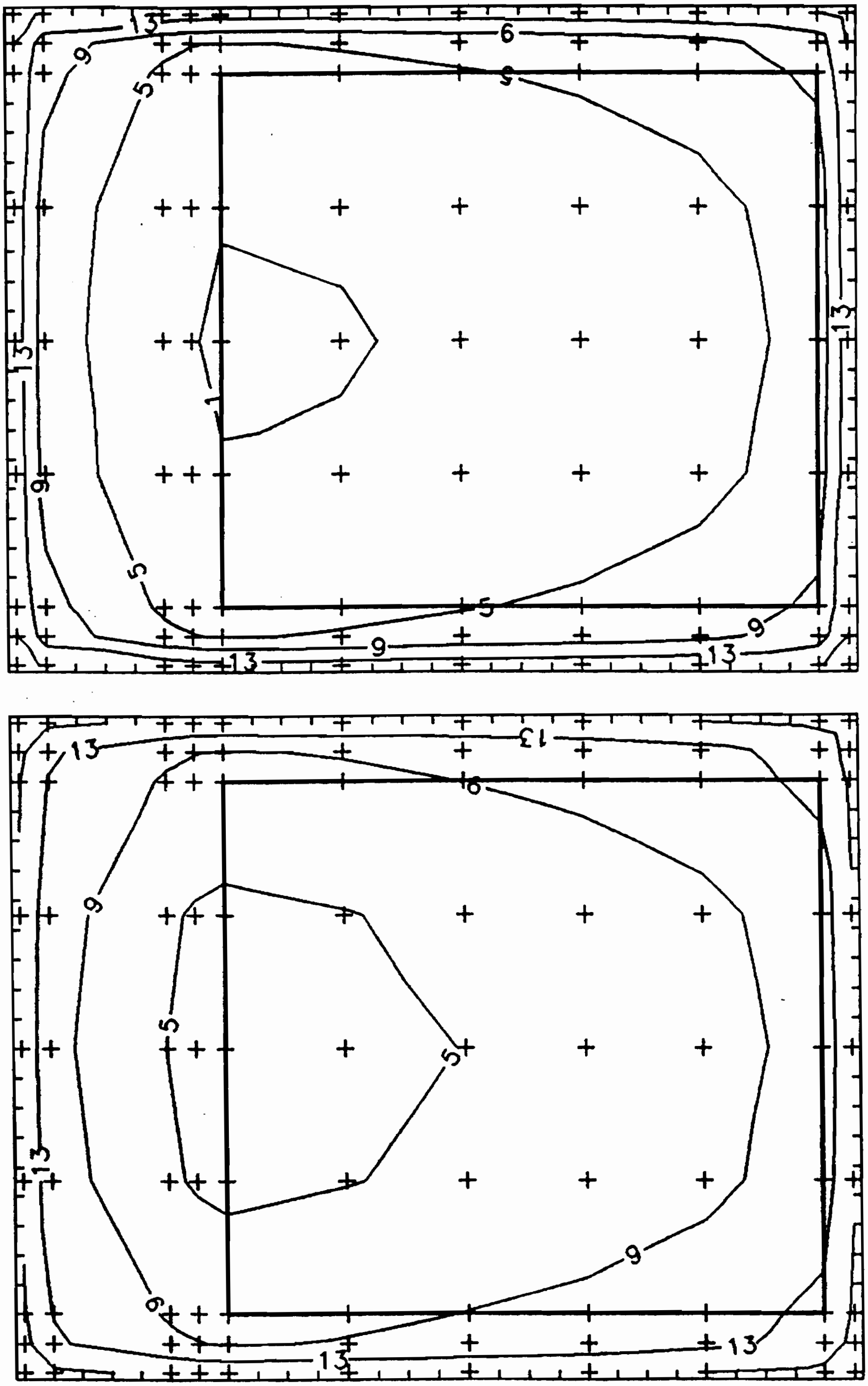

Figure 20. EQ container model at 24 hours for LA flight; icing method 1.

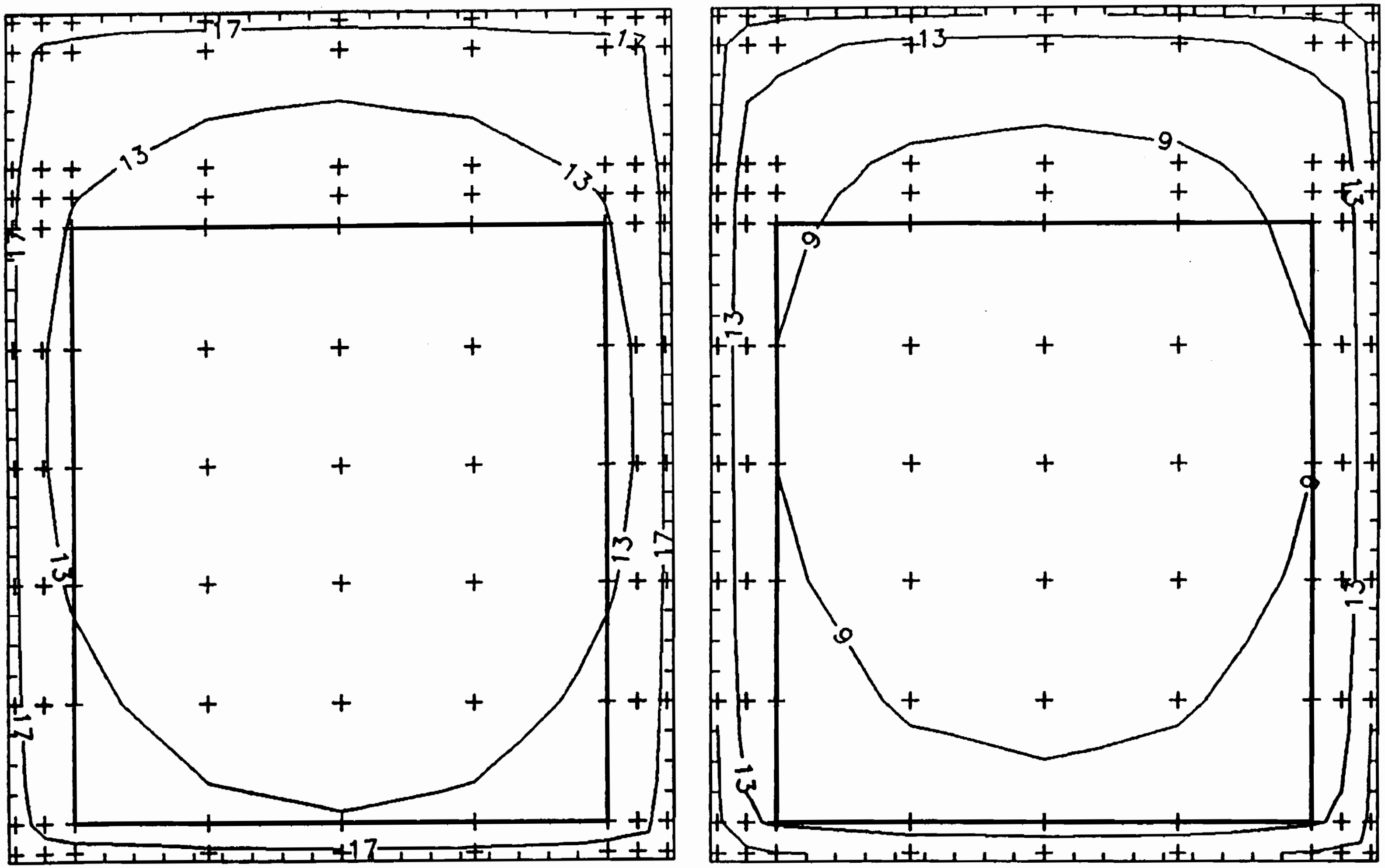

Figure 21. EQ container model at 48 hours for LA flight; icing method 1.

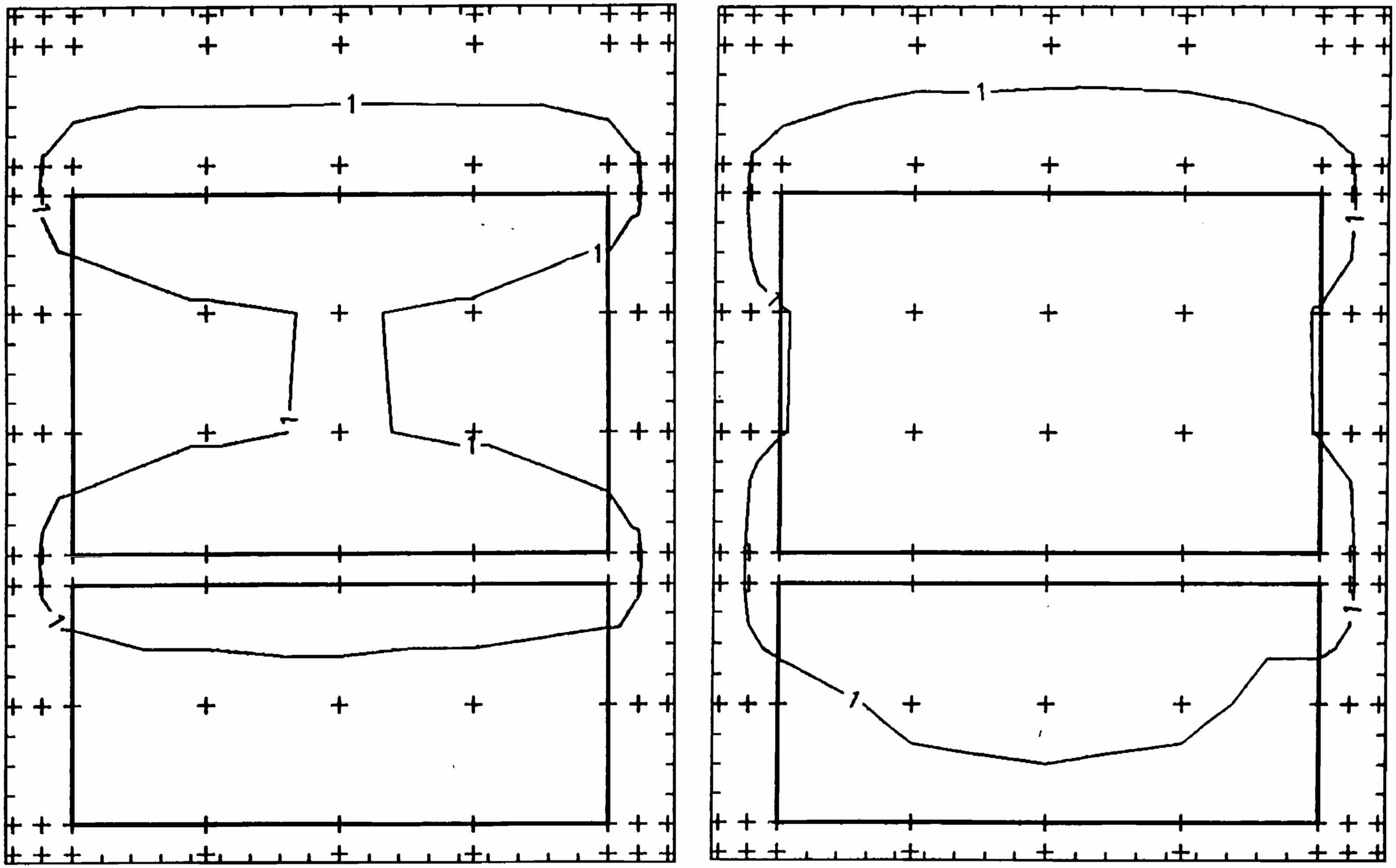

Figure 22. EQ container model at 6 hours for LA flight; icing method 2.

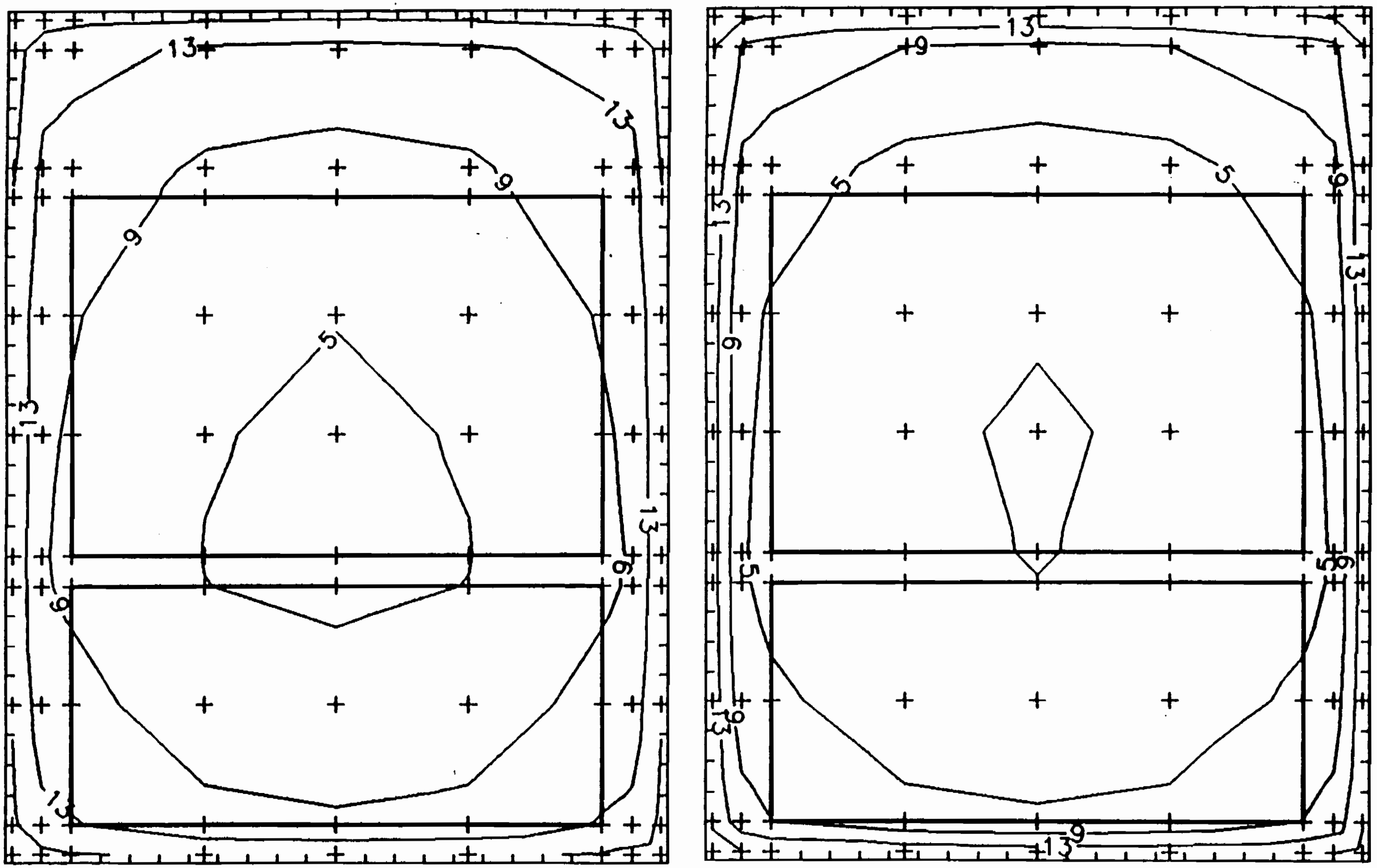

Figure 23. EQ container model at 24 hours for LA flight; icing method 2.

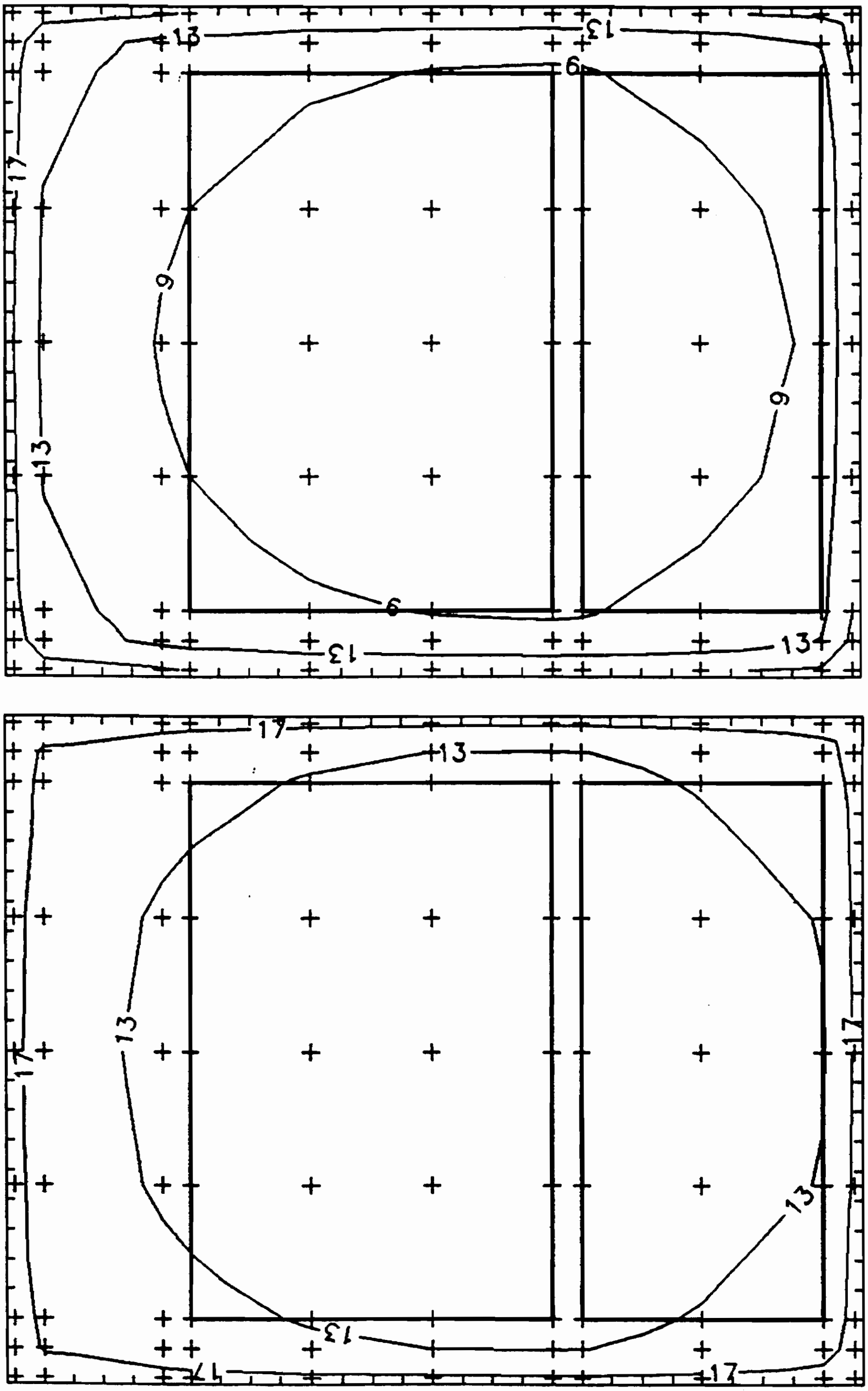

Figure 24. EQ container model at 48 hours for LA flight; icing method 2.

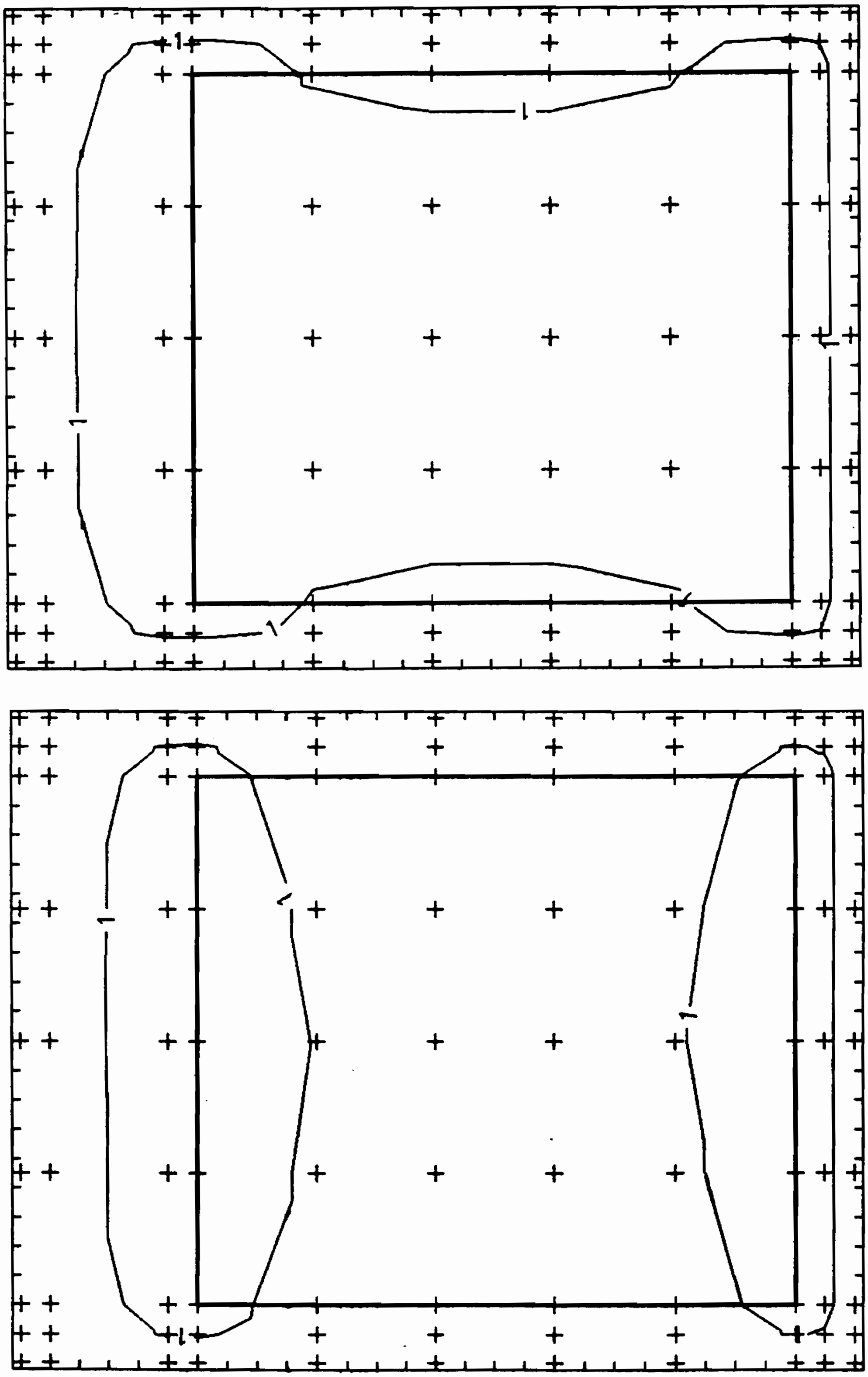

Figure 25. EQ container model at 6 hours for LA flight; icing method 3.

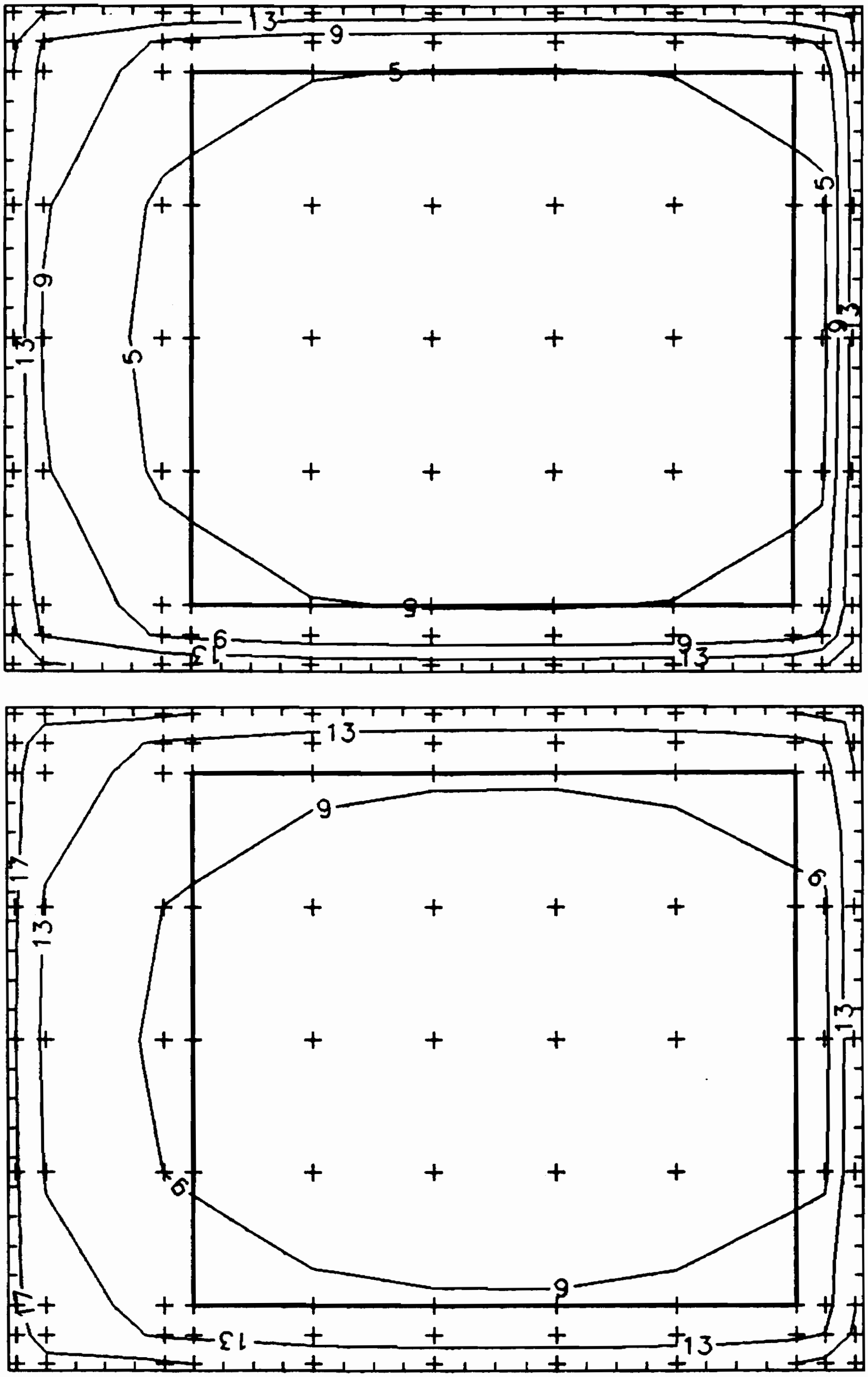

Figure 26. EQ container model at 24 hours for LA flight; icing method 3.

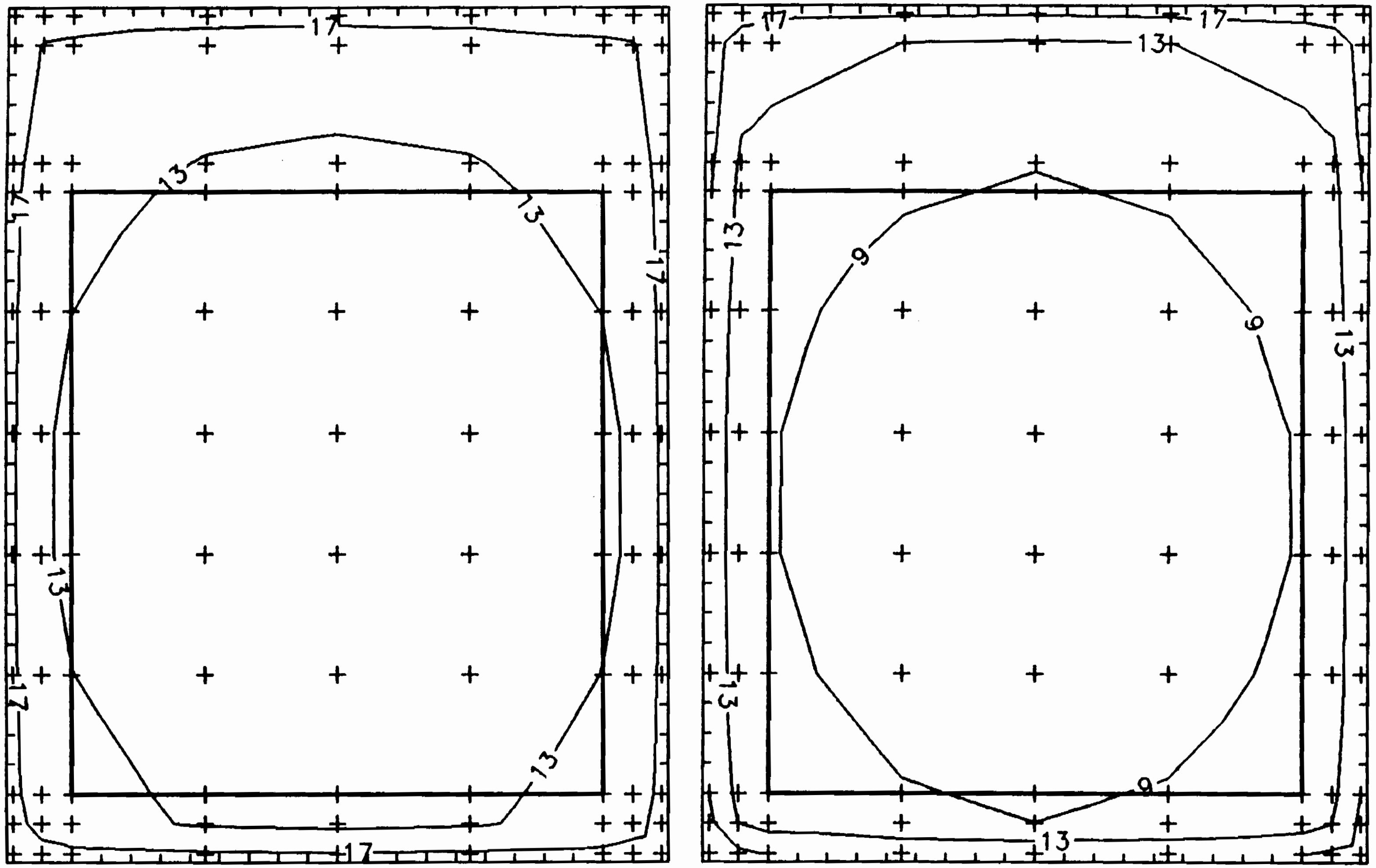

Figure 27. EQ container model at 48 hours for LA flight; icing method 3.

Chapter 6

Conclusions

Below is a list of the conclusions that may be drawn from this work:

1. "10-pound" boxes may be cooled in a cooler with if frequently shaken in approximately 3.5 hours from 30°C.

2. If the cooler is not shaken cooling in ice will be approximately 12 hours.

3. "20-pound" boxes and "10-pound" bags will require approximately 18 hours to cool without shaking.

4. Cooling a "10-pound" box in a refrigerator is effective if high velocity air is maintained as the boundary condition. It will take approximately 6 hours to cool a "10-pound box under these conditions.

5. Cooling a "10-pound" box under still or low velocity air conditions will take approximately 24 hours.

6. The gel packs tested under the conditions of this study showed no advantage over ice.

7. The temperatures encountered during shipment may fall above 35°C (95°F)

8. Of the three ice placements tested splitting the ice in half and placing half on top of the product and half on the bottom of the product resulted in the lowest temperature throughout the container.

The following suggestions are recommended in making an air shipment of seafood:

1. Pre-chill the product to 32°F (0°C) prior to shipping.

2. Use of "10-pound" or "20-pound" containers will help keep the product in good condition, because the handling will have less effect on the seafood.

3. Place ice in the position described in the conclusions above.

4. Use sufficient ice or gel packs so that the shipment will remain at a low temperature. This volume will vary with the quantity of fish and the time of year.

5. Good communications should be maintained between the shipper, the person receiving the shipment, and the airlines personnel responsible for its delivery so that product may be received in the best possible condition.

The following are recommendations for further research in the area of fresh seafood transportation by air:

1. A shaker table should be looked into for the shaking of a cooler containing "10-pound" boxes for pre-chilling.

2. Actual tests should be conducted on the cooling of product in "10-pound" boxes, "10-pound" bags, and "20-pound" boxes, especially under conditions other than constant temperature boundary conditions.

3. The model developed should be modified to see if increased insulation has a very favorable effect on product temperature.

4. More shipments should be made and the data analyzed.

5. A study of shipping times should be conducted so processors can estimate the amount of time a shipment will take to arrive at its destination.

6. The amount of gel packs required for shipment should be investigated further.

References

American Society of Heating Refrigeration and Air-Conditioning Engineers. 1985. *Handbook of Fundamentals*. Chapters 23, 31, 39.

Baran, N.M. 1988. *Finite Element Analysis on Microcomputers*. McGraw-Hill Book Co., New York, NY.

Barnett, J. 1988. Fears of flying: how to guard against the pitfalls of air freighting. Seafood Supplier, 1(1):28-32.

Batty, J.C. and Folkman, S.L. 1983. *Food Engineering Fundamentals*. John Wiley and Sons, New York, NY.

Chattopadhyay, P. and Bose, A.N. 1972. Computation of insulation efficiencies of fish transport containers. J. of Food Science, 39:41-43.

Crapo, C. and Paust, B. 1986. Air Transportation of Fresh Fish: A Primer for Shippers and Cargo Handlers. Unpublished report, Alaska.

Cook, D.W. and Ruple, A.D. 1989. Indicator bacteria and Vibrionaceae multiplication in post-harvest shellstock oysters. J. of Food Protection, 52(5):343-349.

Dietrick D. 1990. Personal conversation. Swanson Analysis Systems Inc., Houston, PA.

Geankoplis, C.J. 1983. *Transport Processes and Unit Operations*. Allyn and Bacon, Inc., Boston, MA.

Hoff, J.C., W.J. Beck, T.H. Ericksen, G.J. Vasconcelos, and W.M. Pressnell. 1967. Time-temperature effects on the bacteriological quality of stored shellfish. I. Bacteriological changes in live shellfish Pacific oysters, Olympia oysters, Native Littleneck clams, and Manila clams. J. of Food Science. 32:121-124.

Hoff, J.C., W.J. Beck, T.H. Ericksen, G.J. Vasconcelos, and W.M. Pressnell. 1967. Time-temperature effects on the bacteriological quality of stored shellfish. II. Bacteriological changes in shucked Pacific oysters and Olympia oysters. J. of Food Science. 32:125-128.

Huebner, K.H. and Thornton E.A. 1982. *The Finite Element Method for Engineers*. John Wiley and Sons, New York, NY.

Incorpera, F.P. and DeWitt, D.P. 1985. *Fundamentals of Heat and Mass Transfer*. John Wiley and Sons, New York, NY.

Ingraham, J. 1958. Growth of psychrophilic bacteria. J. of Bacteriology, 76:75-80.

International Commission on Microbial Specifications for Foods. 1980. *Microbial Ecology of Foods*, Vol. 2. Food Commodities. Academic Press, New York, NY.

Loncin, M. and Merson, R.L. 1979. *Principles and Selected Applications in Food Engineering*. Academic Press, New York, NY.

Loughran, J. 1987. Personal conversation. Air Cargo, Inc., San Francisco CA.

Martin, R.E. and Flick, G.J. 1990. *The Seafood Industry*. Van Nostrand Reinhold, New York, NY.

Modeland, V. 1989. Fishing for facts on fish safety. Dairy, Food and Environmental Sanitation, 9(6):306-309.

Mohsenin, N.N. 1970. *Physical Properties of Plants and Animal Materials*. Gordon and Breach Science Publishers, New York, NY.

National Fisheries Institute and Air Transport Association of America. 1987. Guidelines for the air shipment of seafood. Washington, D.C.

Rosane, C.H. and Kolbe, E.R. 1986. Handling, scheduling and containerization of live shellfish. Paper No. 6560. American Society of Agricultural Engineers, St. Joseph, MI.

U.S. Department of Commerce. 1989. Fisheries of the United States 1988. Washington, D.C.

Wagner, R.L., Bezanson, A.F. and Peters, J.A. 1969. Fresh fish shipments in the BCF insulated, leakproof container. Commercial Fisheries Review, 31(8-9):41.

Wheaton, F.W. and Lawson, T.B. 1985. *Processing Aquatic Food Products*. John Wiley and Sons, New York, NY.

Appendix A

Solution to the Heat Transfer Equation in General

This appendix is a reprint of parts of Chapter 10: Heat Transfer Problems from *Finite Element Method for Engineers* by Huebner and Thornton.

Introduction

We present a finite element formulation for the computation of the steady-state temperature distribution $T(x,y,z)$ and/or transient temperature distribution $T(x,y,z,t)$ for solids with general surface heat transfer.

Problem Statement

Consider steady-state and/or transient heat transfer in a three-dimensional anisotropic solid Ω bounded by surface Γ . The problem is governed by the energy equation

$$-\left(\frac{\partial q_x}{\partial x}+\frac{\partial q_x}{\partial y}+\frac{\partial q_z}{\partial z}\right) + Q = \rho c_p \frac{\partial T}{\partial t} \qquad [1]$$

where q_x, q_y, and q_z are components of the heat flow rate vector per unit area in Cartesian coordinates (x,y,z) , $Q(x,y,z,t)$ is the internal heat generation rate per unit volume, ρ is the density, and c_p is the specific heat. For an anisotropic medium Fourier's Law is

$$q_x = -\left(k_{11}\frac{\partial T}{\partial x}+k_{12}\frac{\partial T}{\partial y}+k_{13}\frac{\partial T}{\partial z}\right)$$

$$q_y = -\left(k_{21}\frac{\partial T}{\partial x}+k_{22}\frac{\partial T}{\partial y}+k_{23}\frac{\partial T}{\partial z}\right) \qquad [2]$$

$$q_z = -\left(k_{31}\frac{\partial T}{\partial x}+k_{32}\frac{\partial T}{\partial y}+k_{33}\frac{\partial T}{\partial z}\right)$$

where k_{ij} is the symmetric conductivity tensor. The material properties ρ, c_p, and k_{ij} may be temperature dependent. If we substitute Fourier's law, equation 2, into the energy equation, equation 1, we obtain the parabolic heat conduction equation. The heat conduction equation is solved subject to an initial condition and boundary conditions on all portions of the surface. The initial condition specifies the temperature distribution at time zero,

$$T(x,y,z,0) = T_0(x,y,z) \qquad [3]$$

Heat conduction boundary conditions take several forms. These are covered in Appendix E of *Finite Element Method for Engineers* by Huebner and Thornton and will not be covered in this thesis. Consider the frequently encountered conditions of specified surface temperature, specified surface heat flow, convective heat exchange, and radiation heat exchange. The boundary conditions are:

$$T_s = T_1\,(x,y,z,t) \qquad \text{on } S_1 \qquad [4a]$$

$$q_x n_x + q_y n_y + q_z n_z = -q_s \qquad \text{on } S_2 \qquad [4b]$$

$$q_x n_x + q_y n_y + q_z n_z = h(T_S - T_e) \qquad \text{on } S_3 \qquad [4c]$$

$$q_x n_x + q_y n_y + q_z n_z = \sigma\varepsilon T_S^4 - \alpha q_r \qquad \text{on } S_4 \qquad [4d]$$

where T_1 is the specified surface temperature, which may vary with time, n_x, n_y, and n_z are the direction cosines of the outward normal to the surface, q_S is the specified heat flow rate per unit area (positive into the surface), h is a convective heat transfer coefficient that may be a function of the convective exchange temperature T_e and/or time, T_S is the unknown surface temperature, σ is the Stefan-Boltzman constant, ε is the surface emissivity, which may be a function of the surface temperature, α is the surface absorbtivity, and q_r is the incident radiant heat flow rate per unit area.

Finite Element Formulation

The solution domain Ω is divided into M elements of r nodes each. By the usual procedure we express the temperature and temperature gradients within each element as

$$T^{(e)}(x,y,z,t) = \sum_{i=1}^{r} N_i(x,y,z)\, T_i(t) \qquad [5a]$$

$$\frac{\partial T^{(e)}}{\partial x}(x,y,z,t) = \sum_{i=1}^{r} \frac{\partial N_i}{\partial x}(x,y,z)\, T_i(t) \qquad [5b]$$

$$\frac{\partial T^{(e)}}{\partial y}(x,y,z,t) = \sum_{i=1}^{r} \frac{\partial N_i}{\partial y}(x,y,z)\, T_i(t) \qquad [5c]$$

$$\frac{\partial T^{(e)}}{\partial z}(x,y,z,t) = \sum_{i=1}^{r} \frac{\partial N_i}{\partial z}(x,y,z)\, T_i(t) \qquad [5d]$$

or in matrix notation

$$T^{(e)}(x,y,z,t) = [N(x,y,z)]\,\{T(t)\} \qquad [6a]$$

$$\begin{bmatrix} \frac{\partial T}{\partial x}(x,y,z,t) \\ \frac{\partial T}{\partial y}(x,y,z,t) \\ \frac{\partial T}{\partial z}(x,y,z,t) \end{bmatrix} = [B(x,y,z)]\,\{T(t)\} \qquad [6b]$$

where $[N]$ is the temperature interpolation matrix, $[B]$ is the temperature-gradient interpolation matrix

$$[N(x,y,z)] = [N_1 \;\; N_2 \;\; \dots \;\; N_r] \qquad [7a]$$

$$[B\,(x,y,z)] = \begin{bmatrix} \frac{\partial N_1}{\partial x} & \frac{\partial N_2}{\partial x} & \dots & \frac{\partial N_r}{\partial x} \\ \frac{\partial N_1}{\partial y} & \frac{\partial N_2}{\partial y} & \dots & \frac{\partial N_r}{\partial y} \\ \frac{\partial N_1}{\partial z} & \frac{\partial N_2}{\partial z} & \dots & \frac{\partial N_r}{\partial z} \end{bmatrix} \qquad [7b]$$

$T_i(t)$ is the value of the temperature at each node and $\{T(t)\}$ is the vector element nodal temperatures. The second-order heat conduction equation requires only C^0 continuity, and we may use temperature as the only nodal unknown. We focus on a single element and for simplicity omit the superscript (e) . The method of weighted residuals is used to derive the element equations starting with the energy equation, equation 1. For a review of the method of weighted residuals consult Huebner and Thornton Chapter 4. The method of weighted residuals requires

$$\int_{\Omega^{(e)}} \left(\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} - Q + \rho C_p \frac{\partial T}{\partial t} \right) N_i \, d\Omega = 0 \qquad [8]$$

where $\Omega^{(e)}$ is the domain for the element (e). Following the procedures in Chapter 4 of Huebner and Thornton's text, we integrate the term

$$\int_{\Omega^{(e)}} \left(\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} \right) N_i \, d\Omega$$

by Gauss's theorem, which introduces surfaces integrals of the heat flow across the element boundary $\Gamma^{(e)}$. We write the result in rearranged form

$$\int_{\Omega^{(e)}} \rho c_p \frac{\partial T}{\partial t} N_i \, d\Omega - \int_{\Omega^{(e)}} \left[\frac{\partial N_i}{\partial x} \quad \frac{\partial N_i}{\partial y} \quad \frac{\partial N_i}{\partial z} \right] \begin{bmatrix} q_x \\ q_y \\ q_z \end{bmatrix} d\Omega =$$

$$\int_{\Omega^{(e)}} Q\, N_i\, d\Omega - \int_{\Gamma^{(e)}} (\mathbf{q}\cdot\hat{n})\, N_i\, d\Gamma, \qquad i = 1, 2, \ldots, r \qquad [9]$$

Next we express the surface integral as the sum of integrals over S_1, S_2, S_3, and S_4 and introduce the boundary conditions, equations 4. Thus

$$\int_{\Omega^{(e)}} \rho c_p \frac{\partial T}{\partial t} N_i\, d\Omega - \int_{\Omega^{(e)}} \begin{bmatrix} \frac{\partial N_i}{\partial x} & \frac{\partial N_i}{\partial y} & \frac{\partial N_i}{\partial z} \end{bmatrix} \begin{bmatrix} q_x \\ q_y \\ q_z \end{bmatrix} d\Omega =$$

$$\int_{\Omega^{(e)}} Q\, N_i\, d\Omega - \int_{S_1} (\mathbf{q}\cdot\hat{n})\, N_i\, d\Gamma + \int_{S_2} q_s\, N_i\, d\Gamma - \int_{S_3} h(T - T_e)\, N_i\, d\Gamma$$

$$- \int_{S_4} \left(\sigma\varepsilon T^4 - \alpha q_r\right) N_i\, d\Gamma \qquad i = 1, 2, \ldots, r \qquad [10]$$

As the last step we introduce the element temperatures from equation 6a and heat flow components from Fourier's law, equation 2. For convenience we first write equation 2 in matrix form,

$$\begin{bmatrix} q_x \\ q_y \\ q_z \end{bmatrix} = - \begin{bmatrix} k_{11} & k_{12} & k_{13} \\ k_{21} & k_{22} & k_{23} \\ k_{31} & k_{32} & k_{33} \end{bmatrix} \begin{bmatrix} \frac{\partial T}{\partial x} \\ \frac{\partial T}{\partial y} \\ \frac{\partial T}{\partial z} \end{bmatrix} \qquad [11]$$

where $[k]$ is the thermal conductivity matrix, and then express the temperature gradients in terms of the nodal temperature through equation 6b:

$$\begin{bmatrix} q_x \\ q_y \\ q_z \end{bmatrix} = -\,[k]\,[B]\,\{T\} \qquad [12]$$

Finally, after some manipulations the resulting element equations become

$$[C]\left\{\frac{dT}{dt}\right\} + \big[\,[K_c] + [K_h] + [K_r]\big]\,\{T\} = \{R_T\} + \{R_Q\} + \{R_q\} + \{R_h\} + \{R_r\} \qquad [13]$$

where

$$[C] = \int_{\Omega^{(e)}} \rho c_p\,\{N\}\,[N]\,d\Omega \qquad [14a]$$

$$[K_c] = \int_{\Omega^{(e)}} [B]^T\,[k]\,\,[B]d\Omega \qquad [14b]$$

$$[K_h] = \int_{S_3} h\,\{N\}\,[N]\,d\Gamma \qquad [14c]$$

$$[K_r]\,\{T\} = \int_{S_4} \sigma\varepsilon T^4\,\{N\}\,d\Gamma \qquad [14d]$$

$$\{R_T\} = -\int_{S_1} (\mathbf{q}\cdot\hat{n})\,\{N\}\,d\Gamma \qquad [15a]$$

$$\{R_Q\} = -\int_{\Omega} Q\{N\}\, d\Omega \qquad [15b]$$

$$\{R_q\} = -\int_{S_2} q_s\{N\}\, d\Gamma \qquad [15c]$$

$$\{R_h\} = -\int_{S_3} hT_e\,\{N\}\, d\Gamma \qquad [15d]$$

$$\{R_r\} = -\int_{S_3} \alpha q_r\,\{N\}\, d\Gamma \qquad [15e]$$

The coefficient matrix $[C]$ of the time derivative of the nodal temperatures is the element capacitance matrix. The coefficient matrices $[K_c]$, $[K_h]$, and $[K_r]$ are the element conductance matrices and relate to conduction, convection, and radiation respectively. The convection and radiation matrices are computed only for elements with surface convection and/or radiation. The vectors $\{R_T\}$, $\{R_q\}$, $\{R_h\}$, and $\{R_r\}$ are heat load vectors arising from specified nodal temperatures, internal heat generation, specified surface heating, surface convection, and incident surface radiant heating, respectively. The vector $\{R_T\}$ represents unknown nodal heat loads applied to maintain the nodes on the surface S_1 at specified temperatures. These heat loads may be computed, if desired, after the assembly of the element equations by the procedure described by Huebner and Thornton in Section 2.3.4. (Ibid pp. 50, 51) The integral definition of $\{R_T\}$, equation 15a, is normally not evaluated and is not considered in subsequent discussion. The convection and radiation heat load vectors, like their corresponding conductance matrices, are computed only for elements with surface convection and/or radiation.

Equations 13 are a general nonlinear formulation of element equations for transient heat conduction in an anisotropic medium. Assembly of the element equations to obtain the system equations follows the standard procedure. Note that since the nodal unknowns T_i are scalars, no transformations of matrices computed in local coordinates are necessary before assembly of the global matrices.

For analysis of practical heat conduction problems special cases of the general equations are usually considered, because solution algorithms depend on whether a problem is steady state or transient, or linear or nonlinear. For subsequent discussion the following cases are identified:

Linear steady-state analysis:

$$\left[[K_c] + [K_h] \right] \{T\} = \{R_Q\} + \{R_q\} + \{R_h\} \tag{16}$$

Linear transient analysis:

$$[C] \left\{ \dot{T}(t) \right\} + \left[[K_c] + [K_h(t)] \right] \{T(t)\} = \{R_Q(t)\} + \{R_q(t)\} + \{R_h(t)\} \tag{17}$$

Appendix B

EQ Carton Model Verification

The EQ model was checked by comparing the model predictions with the number of nodes. The next two figures are of the temperature through the center of a box after 10 hours. The first one has a reduced number of nodes. The next two plots are of the temperature though another section. The next four plots are of the heat flows through various sections of the box. They all seem to compare well. The curves may not be as smooth in the case of the reduced node numbers, but they appear to be just as accurate. For this reason and, because there was a significant time increase in running the more refined model on the computer the less refined mesh was used.

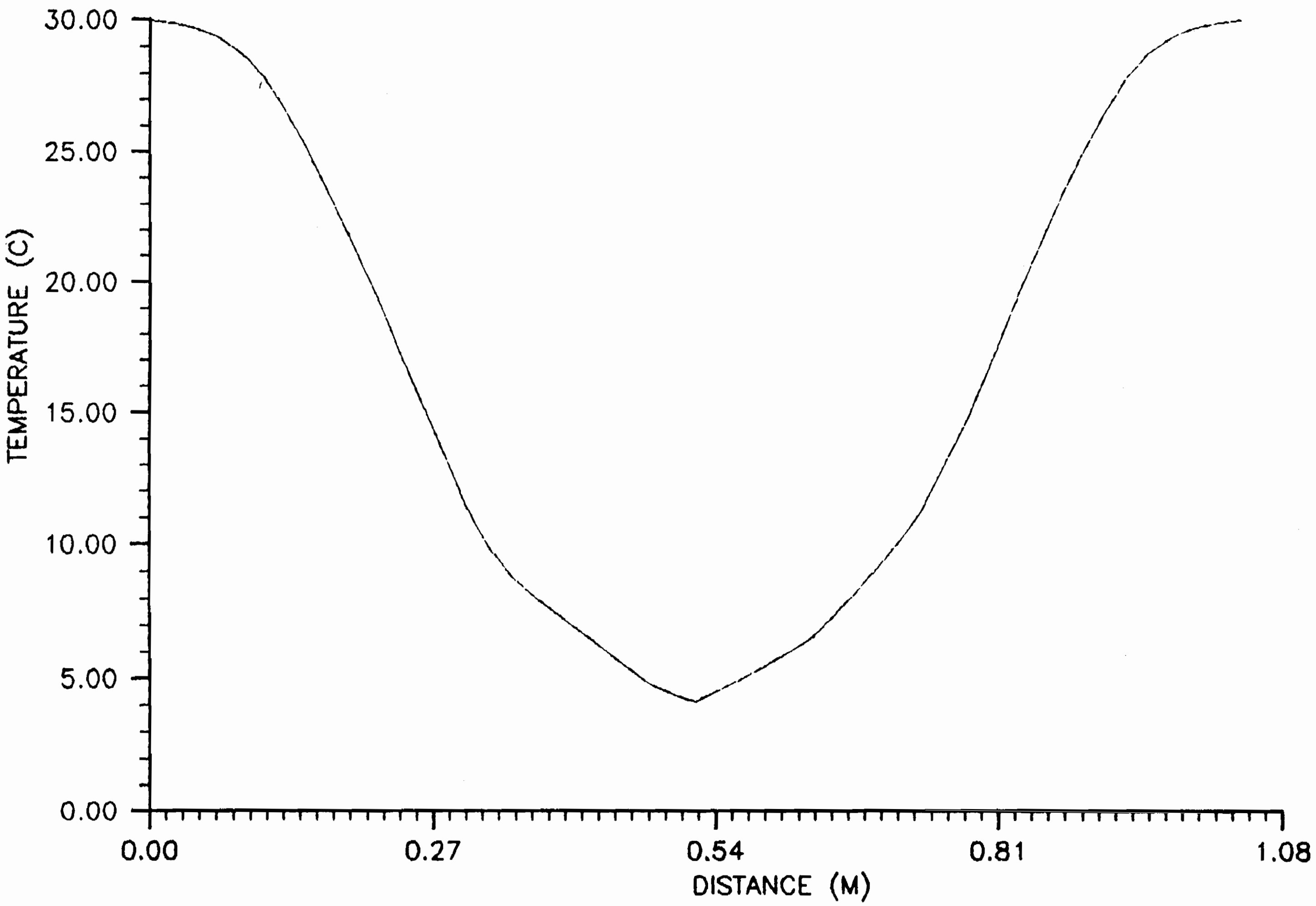

Figure 28. EQ container model with reduced nodes.

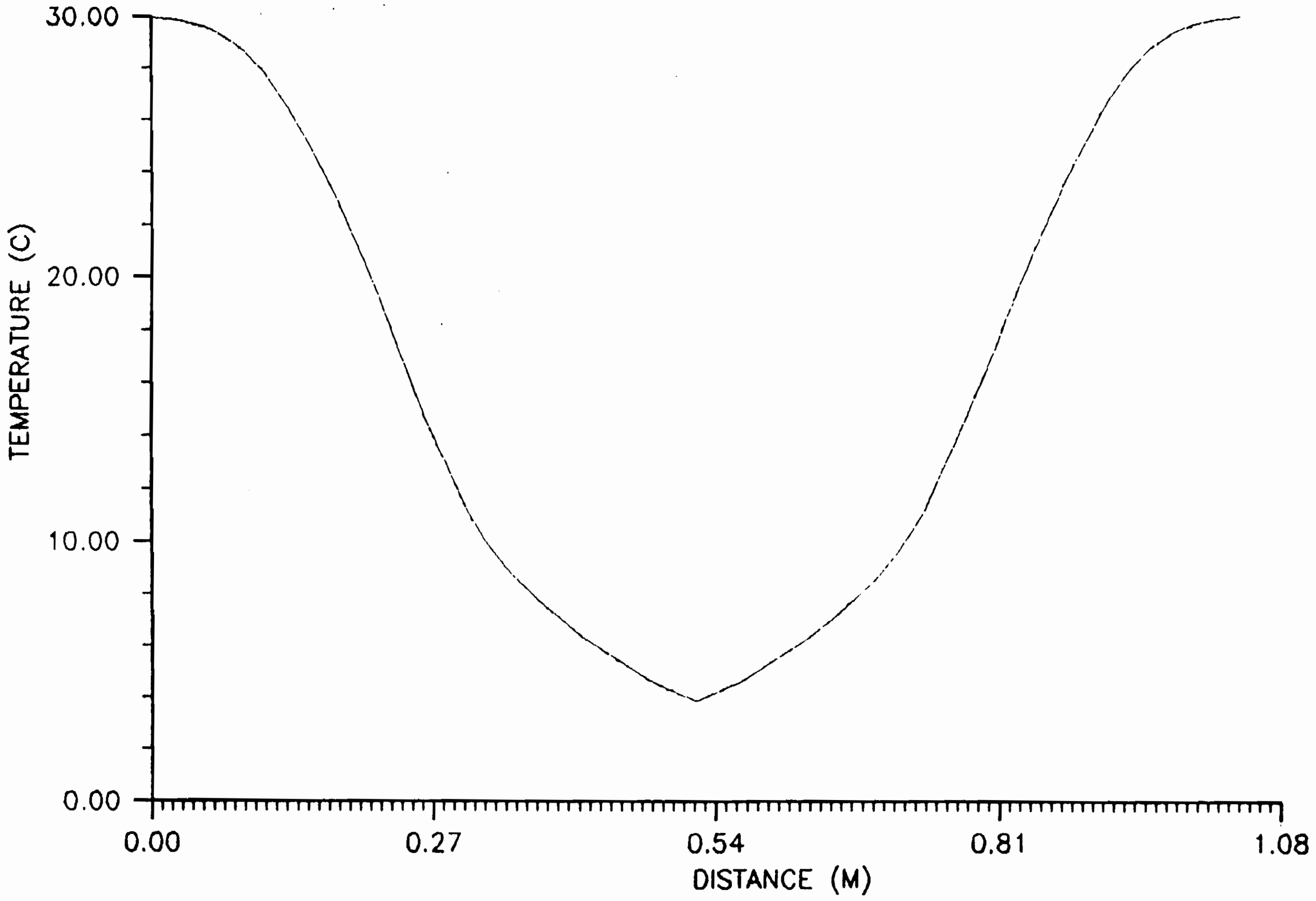

Figure 29. EQ container with increased nodes.

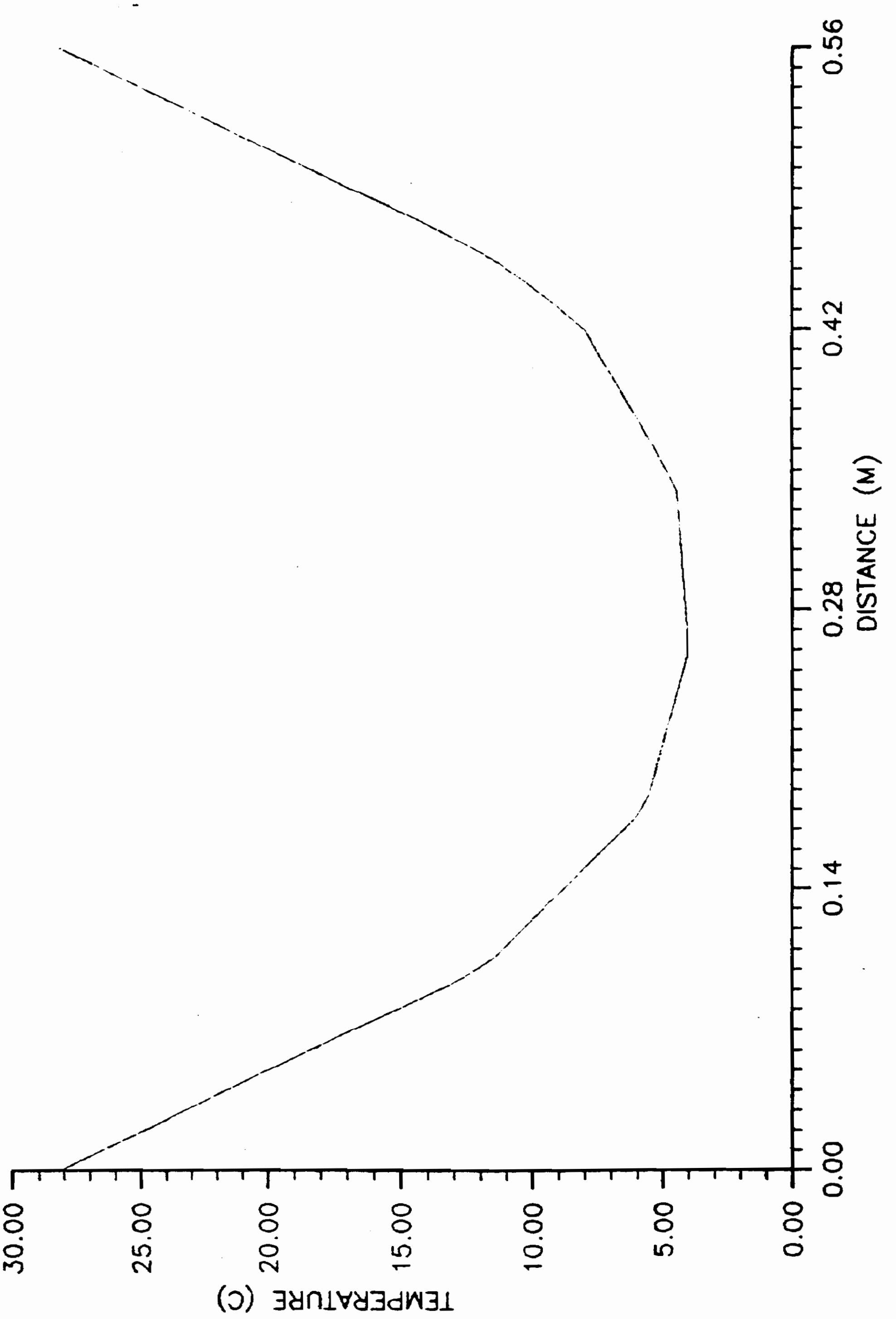

Figure 30. EQ container model with reduced nodes.

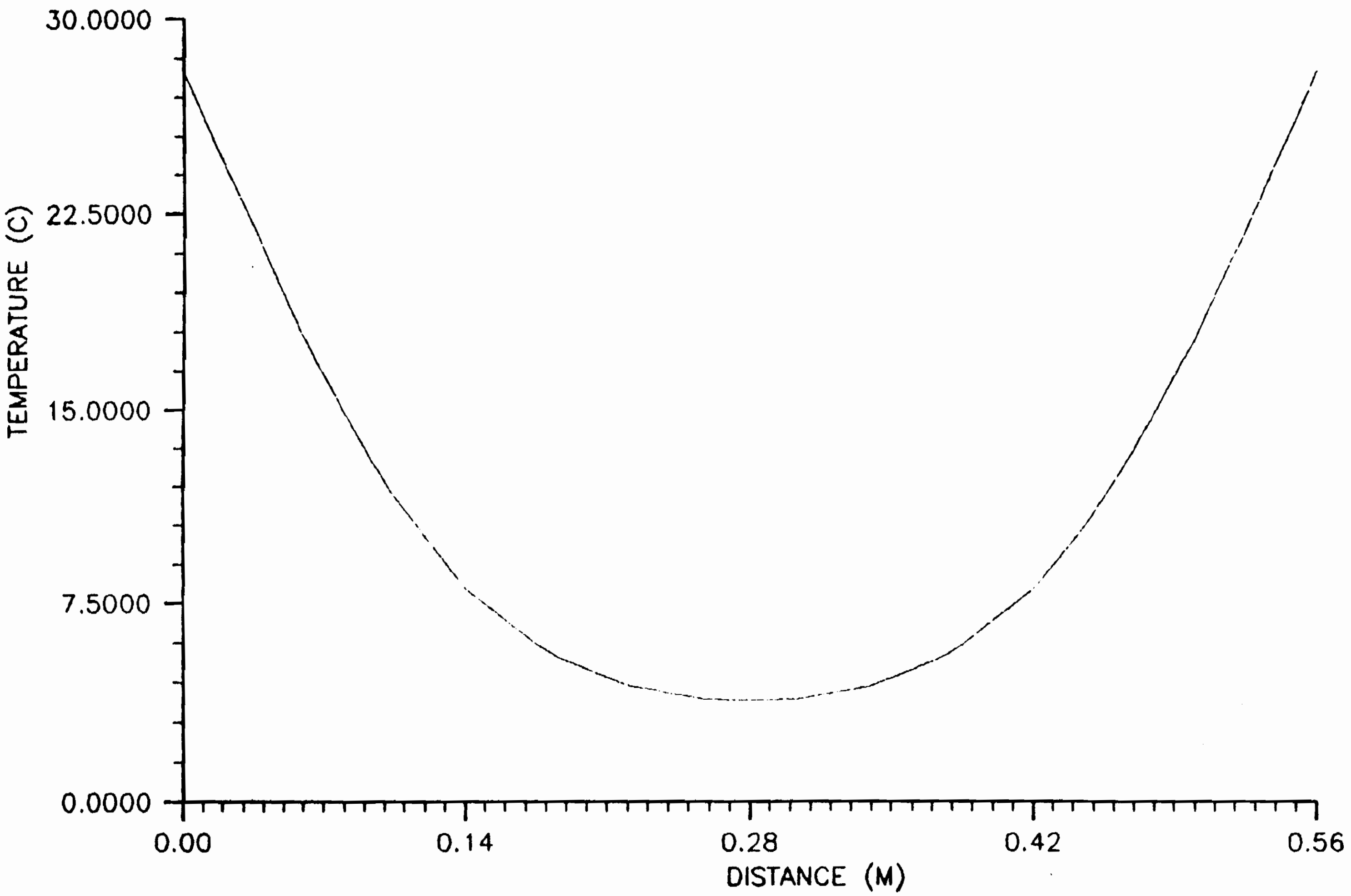

Figure 31. EQ container model with increased nodes.

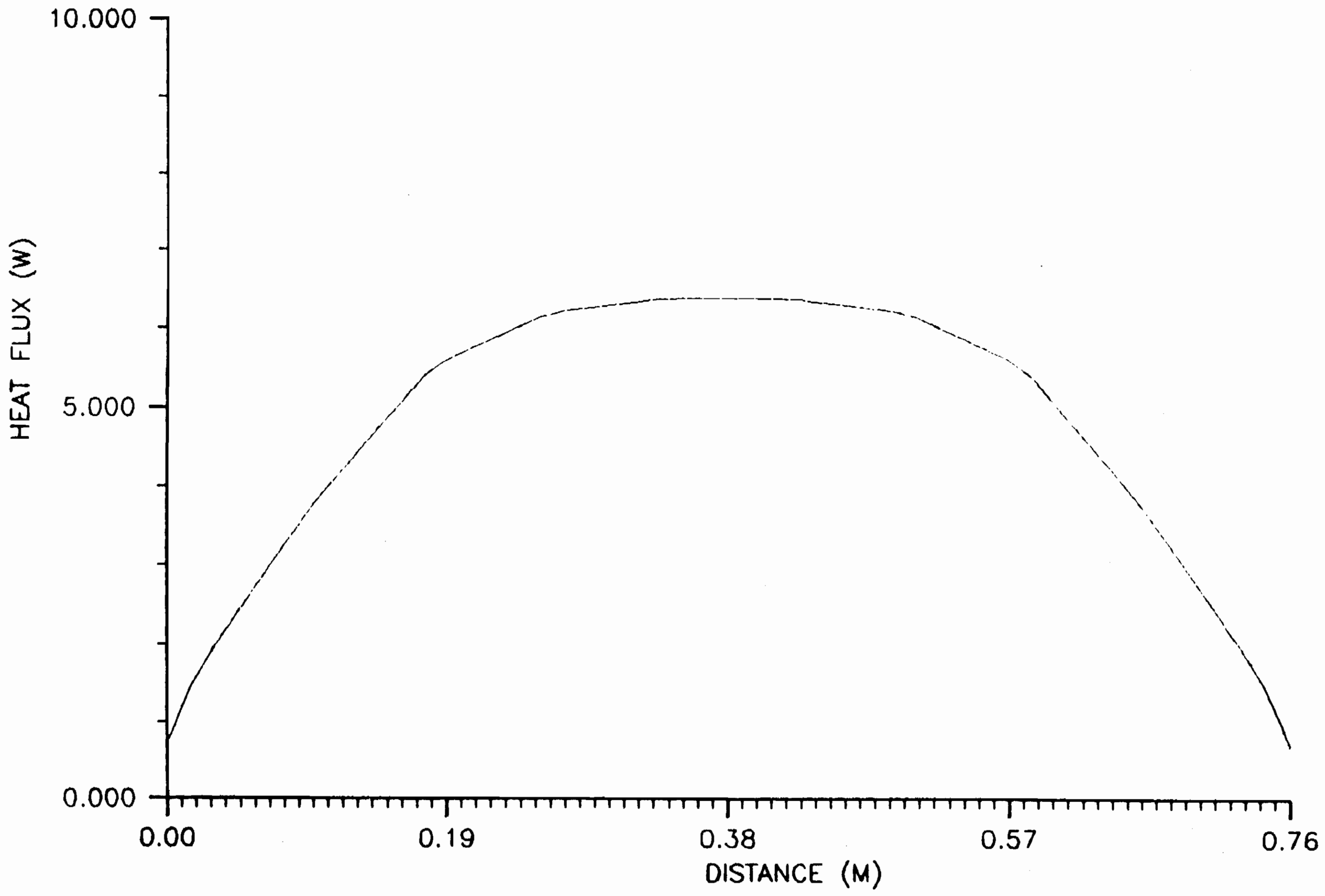

Figure 32. EQ container model with reduced nodes.

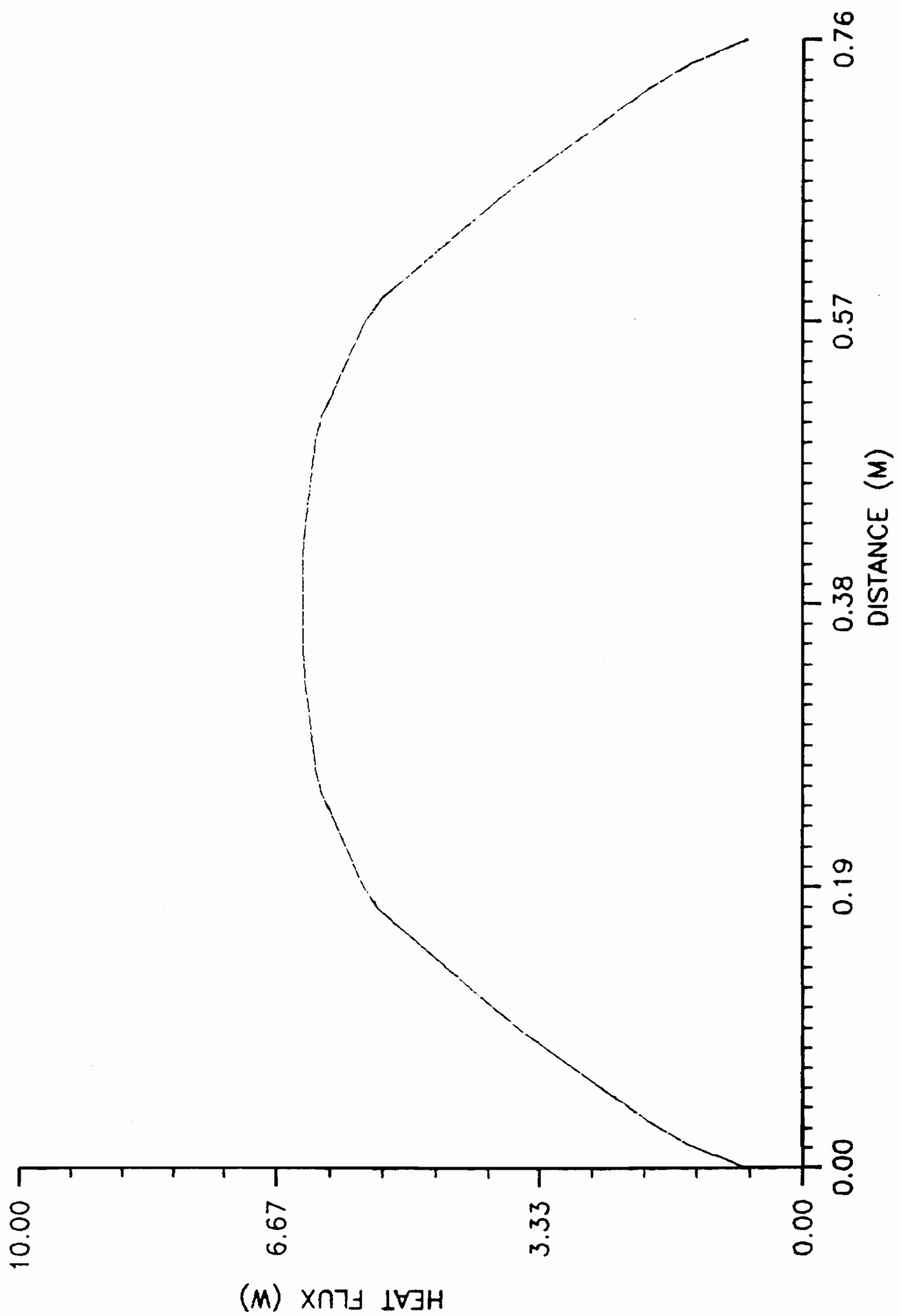

Figure 33. EQ container model with increased nodes.

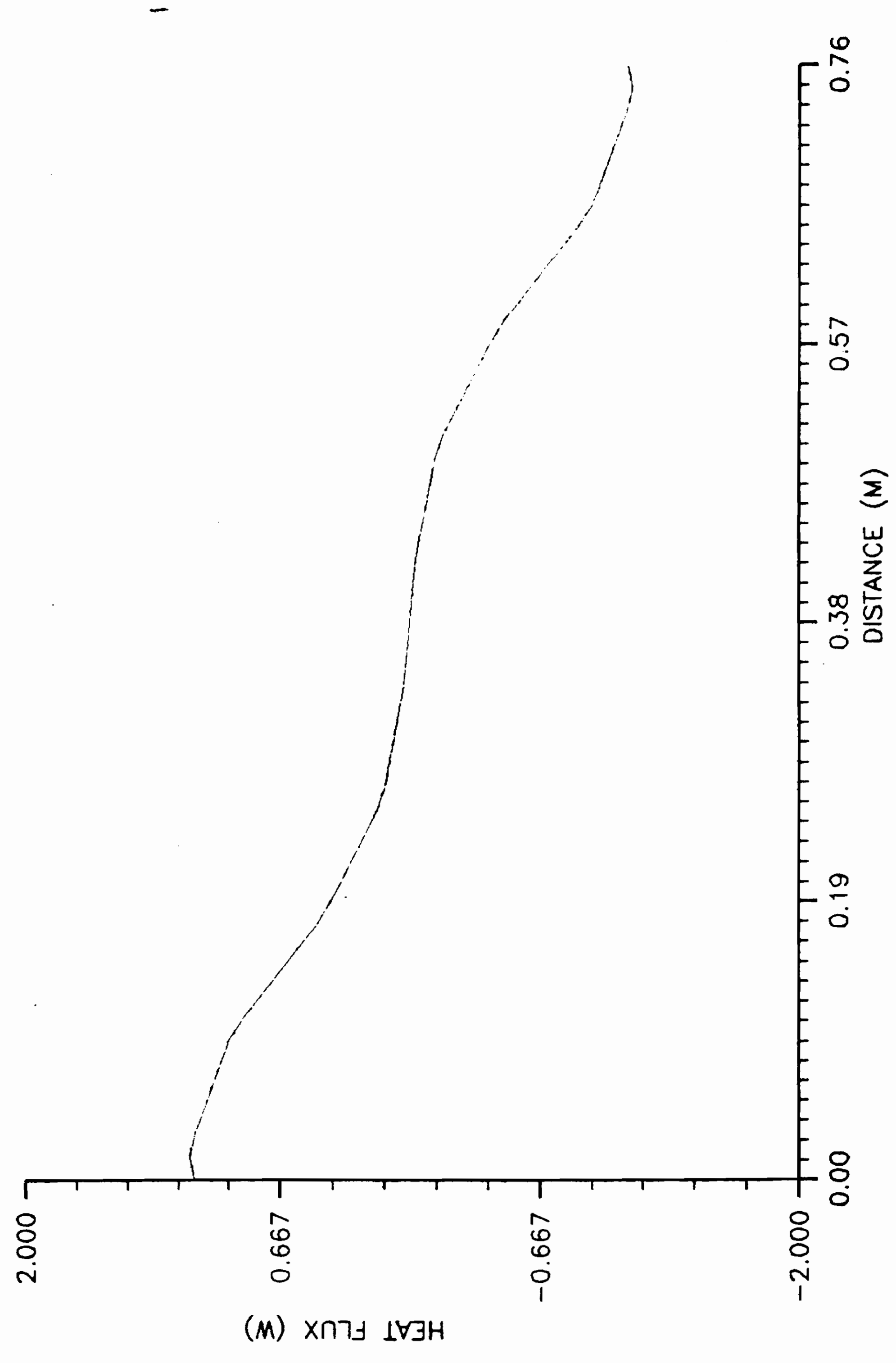

Figure 34. EQ container model with reduced nodes.

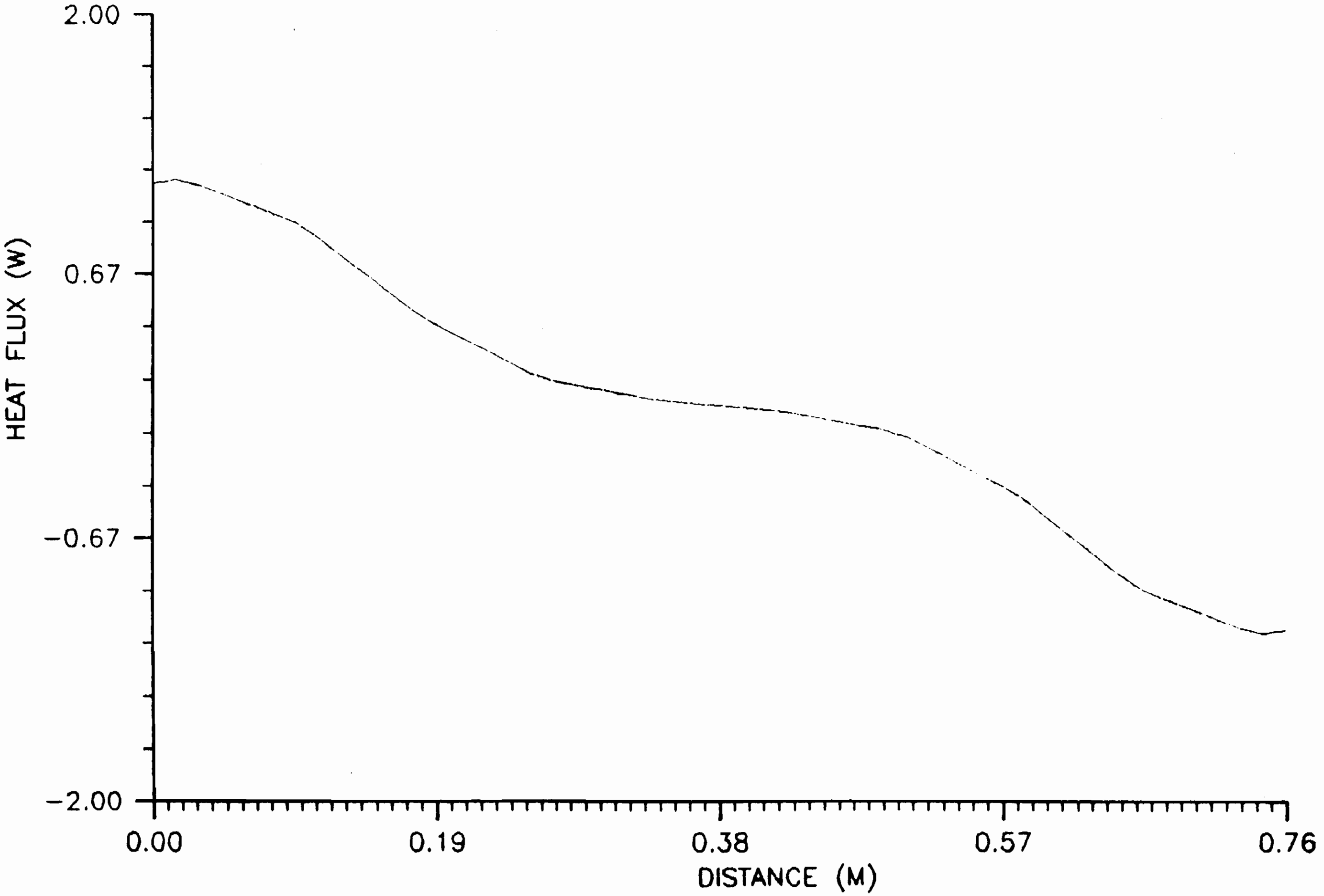

Figure 35. EQ container model with increased nodes.

Appendix C

Cooling Tests on "10-Pound" bags and "20-pound" Boxes

The results for the "10-pound" bag and "20-pound" box appear in the following plot.

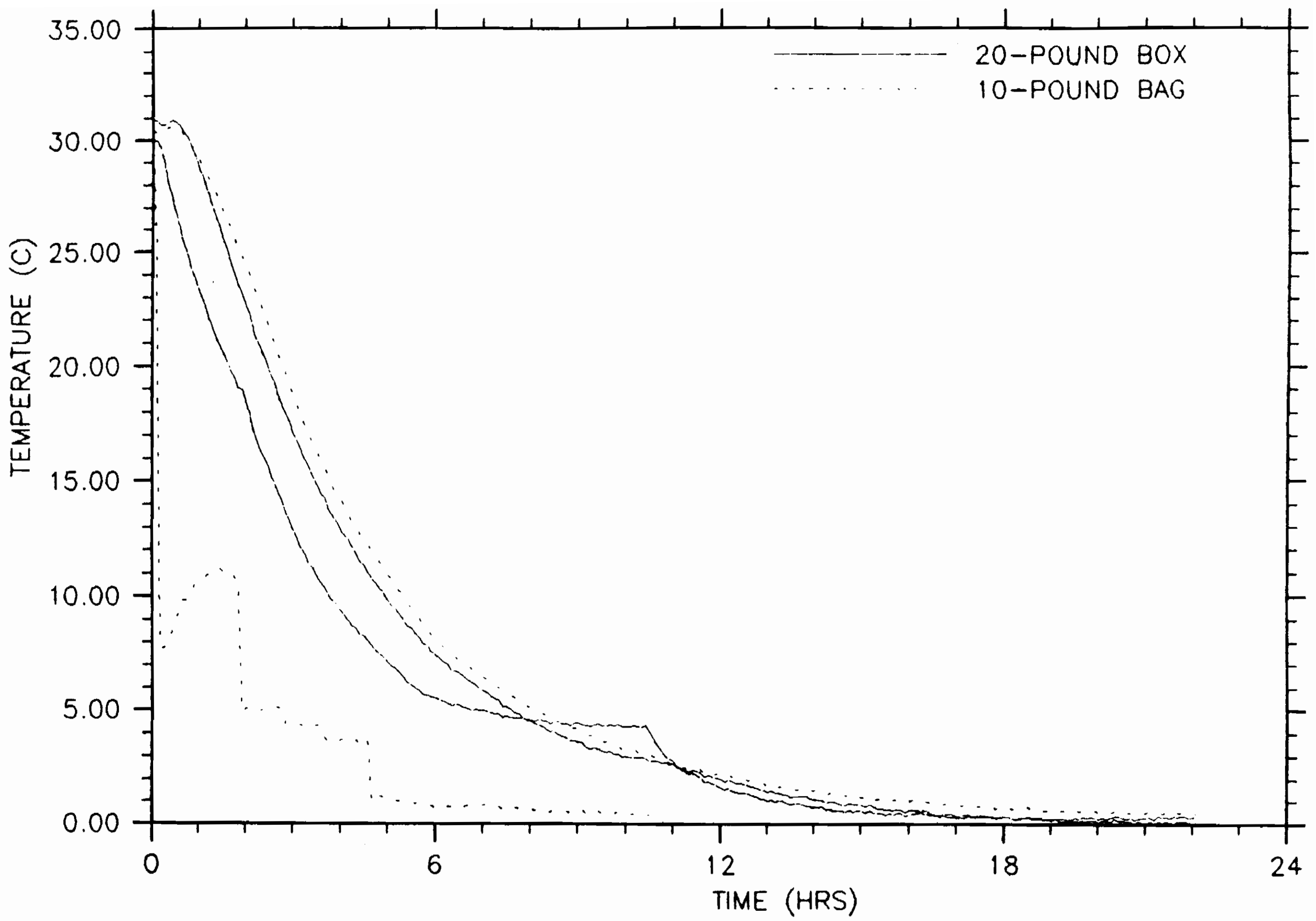

Figure 36. Cooling tests on "10-pound" bags and "20-pound" boxes.

Appendix D

Results of the EQ Shipment Versus Model

The results for the finite element model compared with the actual shipment appear in the next 2 Figures. It is difficult to compare these as equal volumes of ice were not used for the model and the experiments, and in the model it was assumed that the fish would be boxed in "10-pound" boxes and in the experiments the fish were placed in the EQ container in bulk.

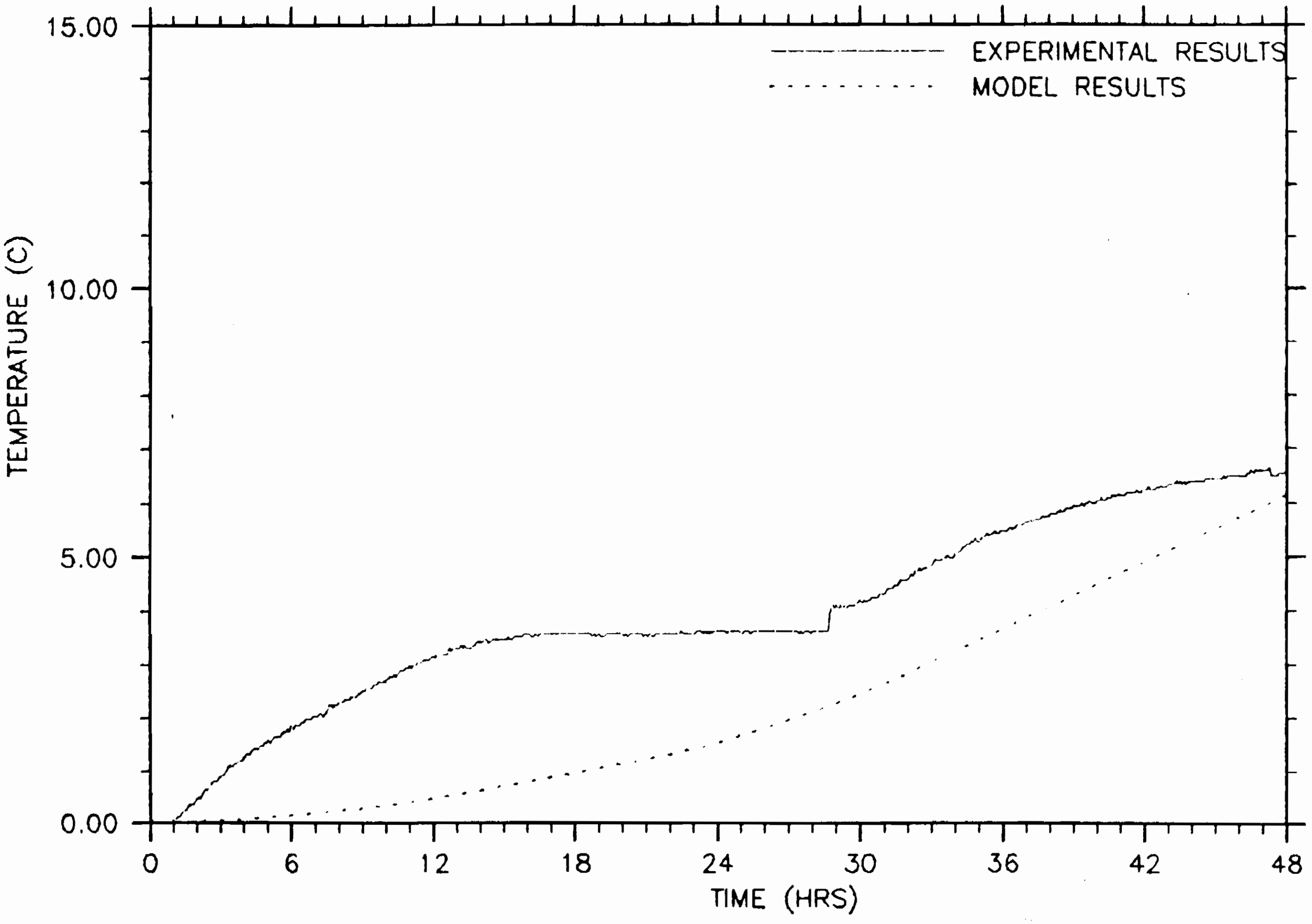

Figure 37. Center temperature of fish for the LA flight.

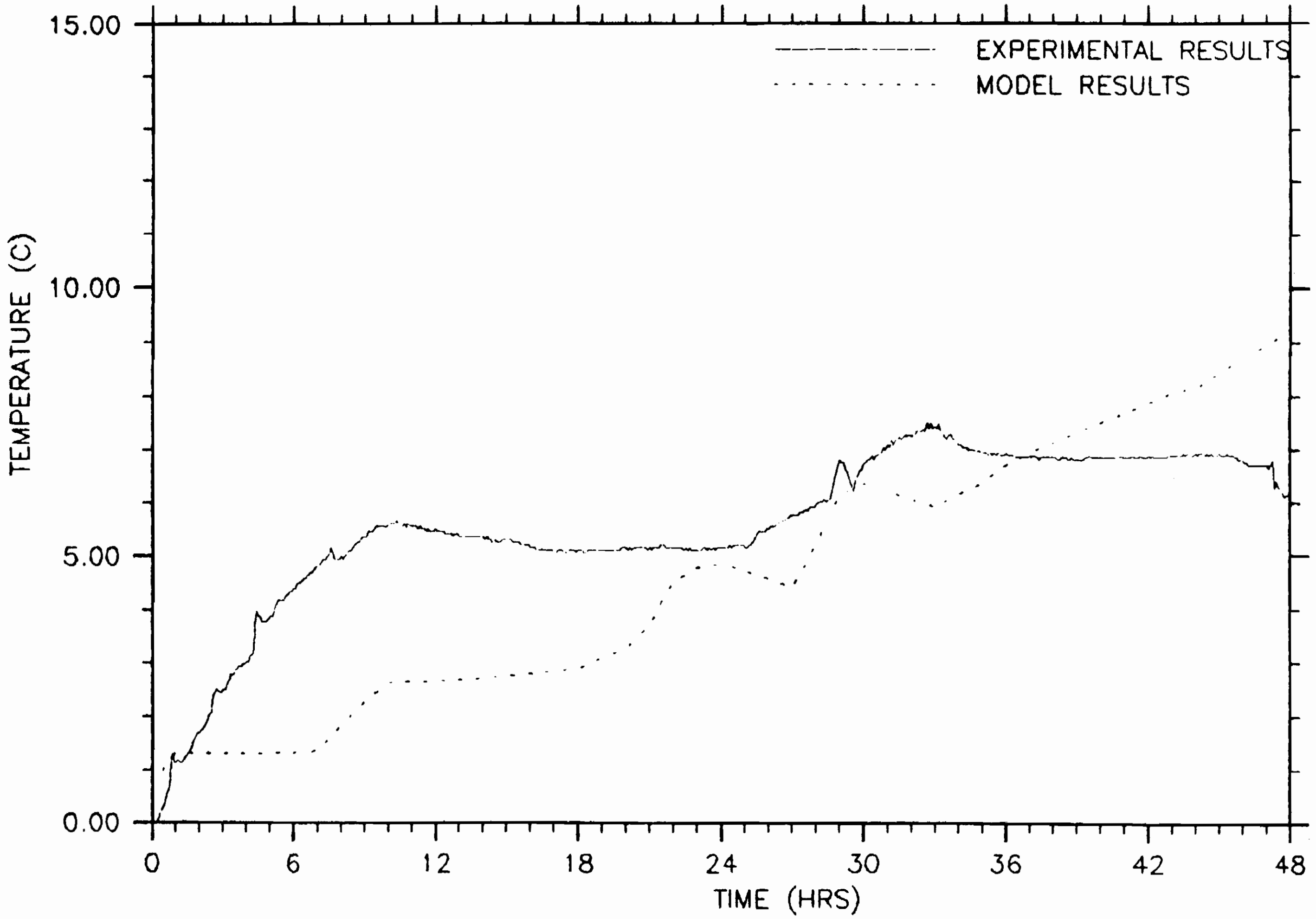

Figure 38. Center temperature of side of the insulation for the LA flight.

Appendix E

Results of the EQ Finite Element Model

The results for the finite element models not shown in Chapter 5 follow. *Ice position 1* refers to all the ice placed on top of the seafood. *Ice position 2* refers to the case where the ice is split between the top of the fish and the second and third "10-pound" boxes from the bottom of the container. *Ice position 1* refers to the case where the ice is placed on top of the fish and on the bottom of the fish.

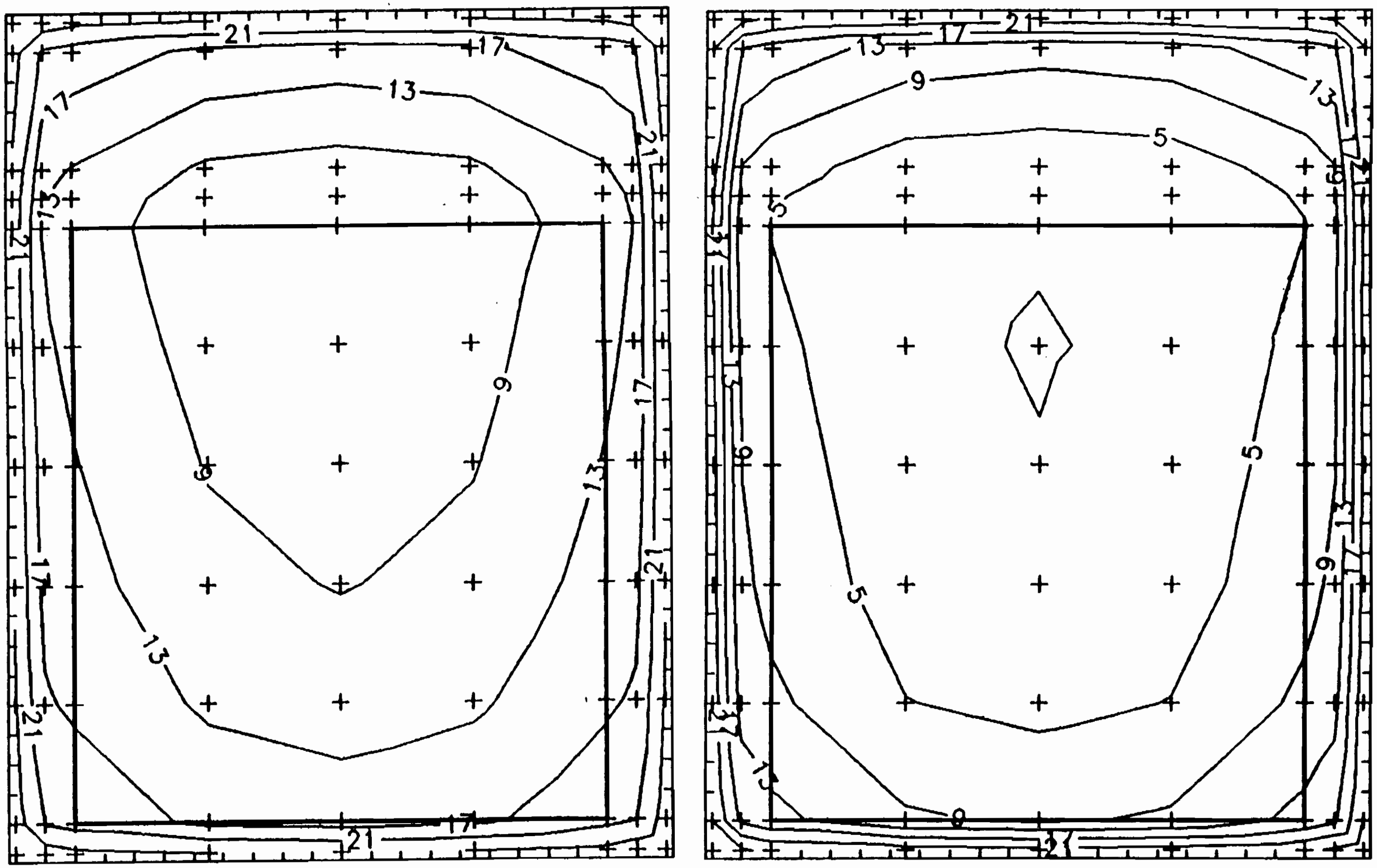

Figure 39. EQ container model at 12 hours with constant boundary conditions; icing method 1.

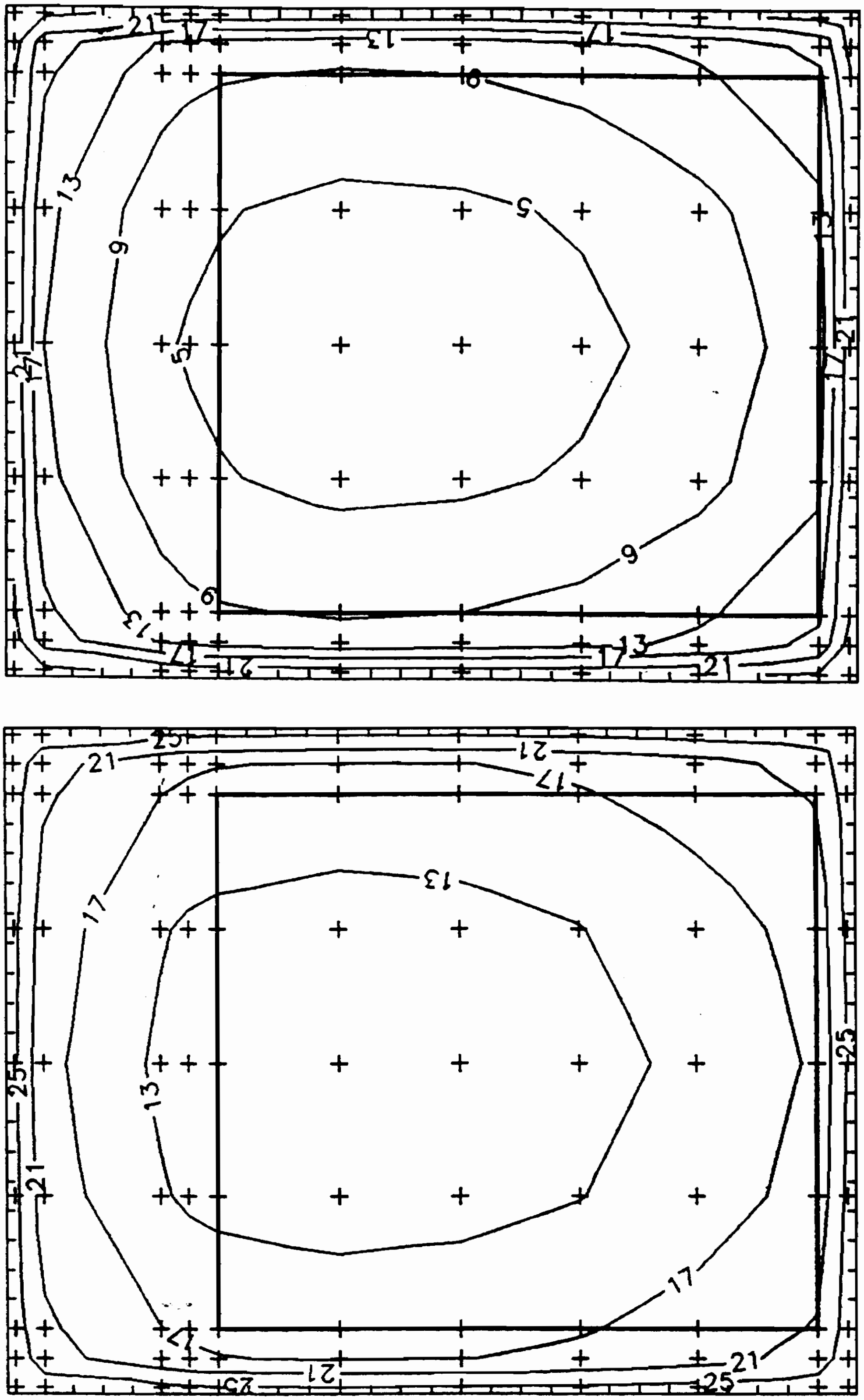

Figure 40. EQ container model at 18 hours with constant boundary conditions; icing method 1.

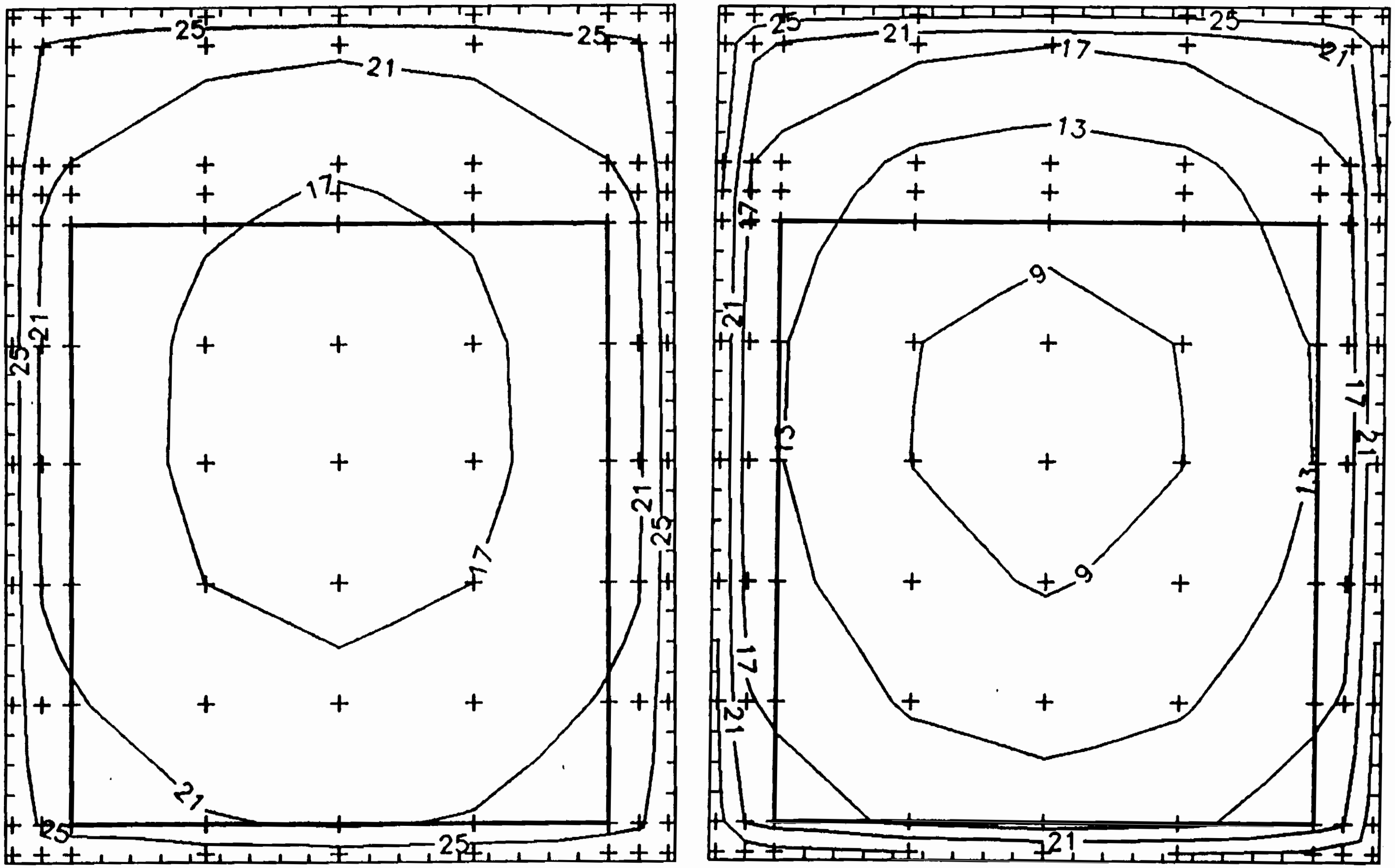

Figure 41. EQ container model at 30 hours with constant boundary conditions; icing method 1.

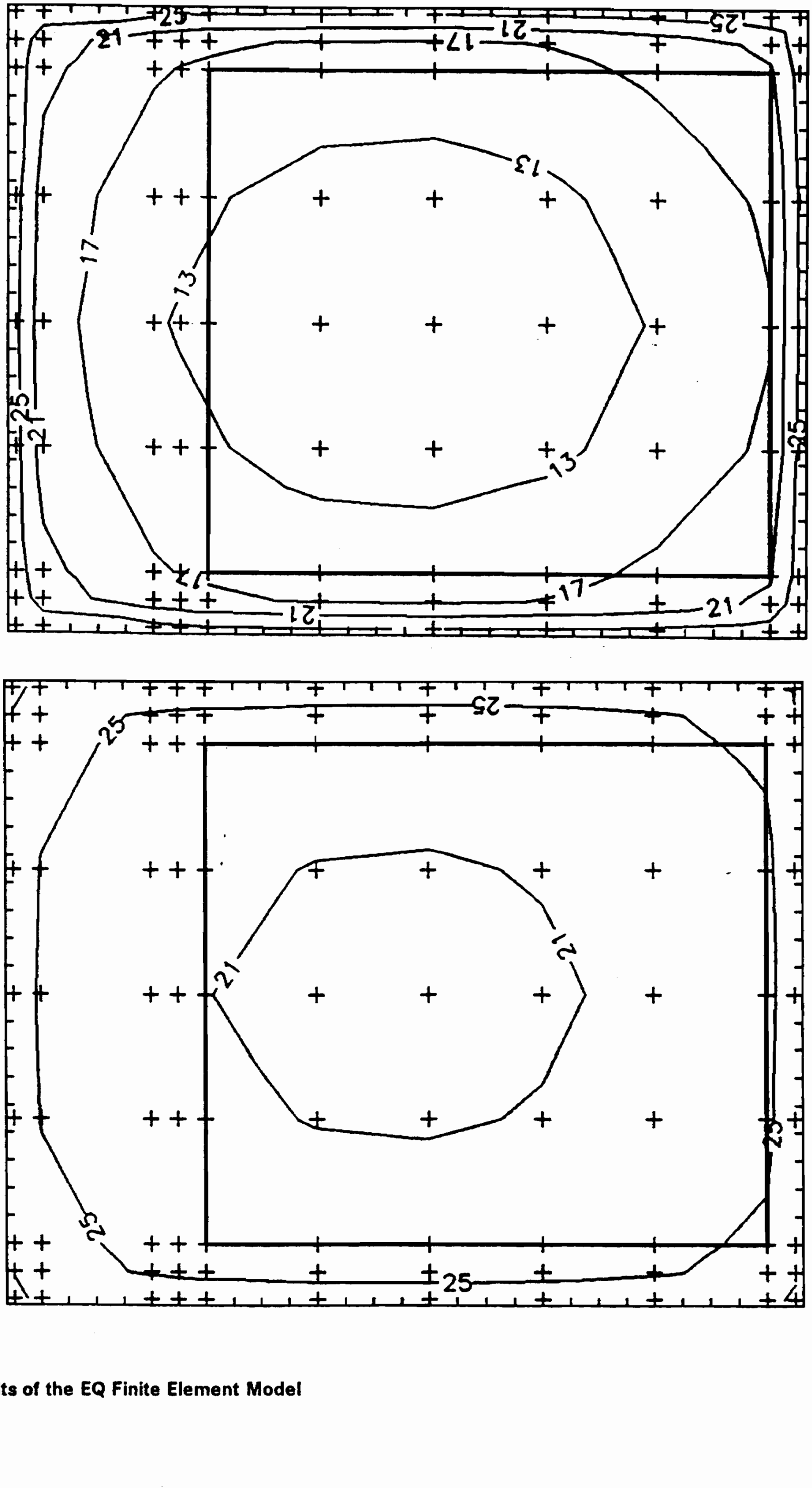

Figure 42. EQ container model at 36 hours with constant boundary conditions; icing method 1.

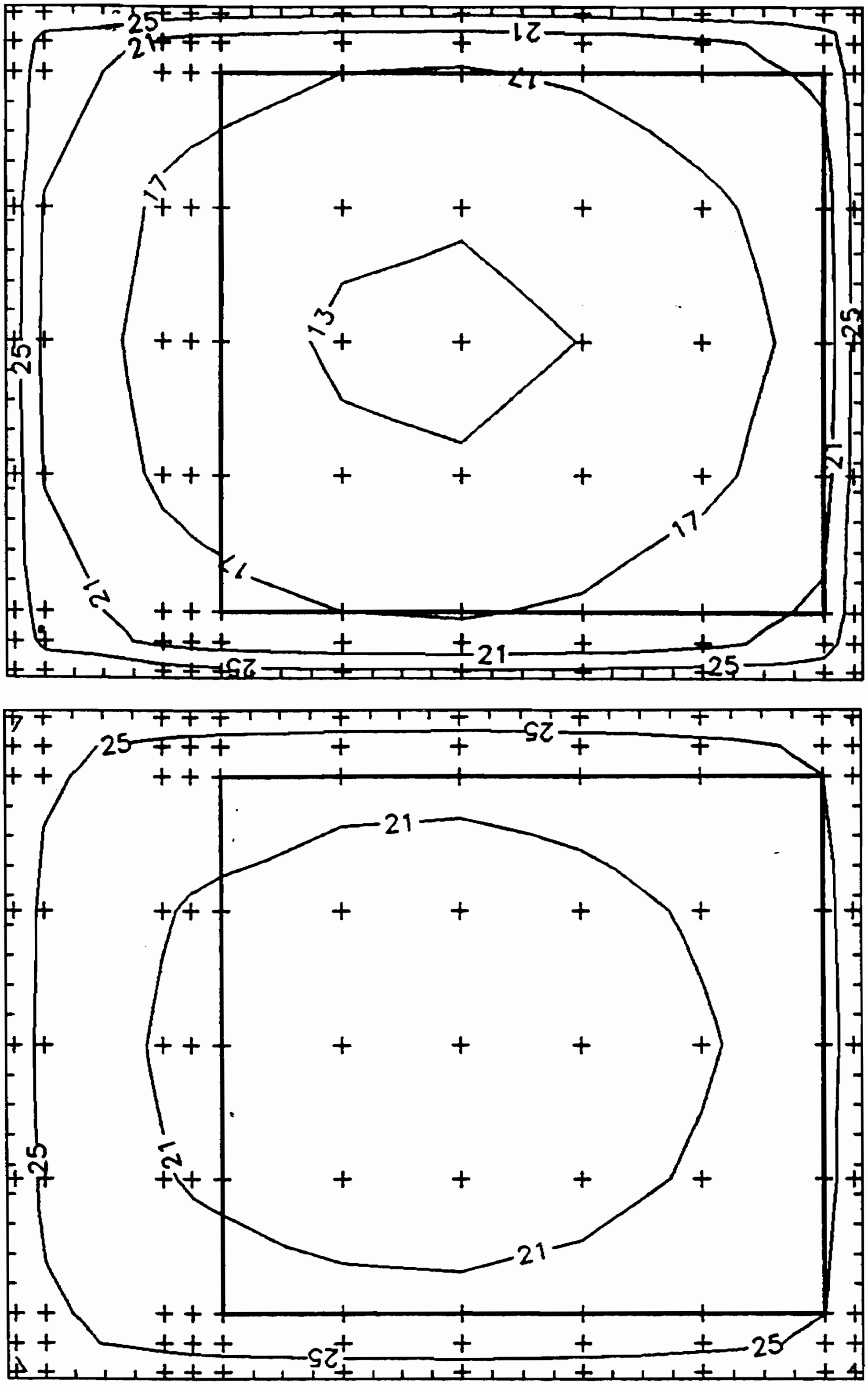

Figure 43. EQ container models at 42 hours with constant boundary conditions; icing method 1.

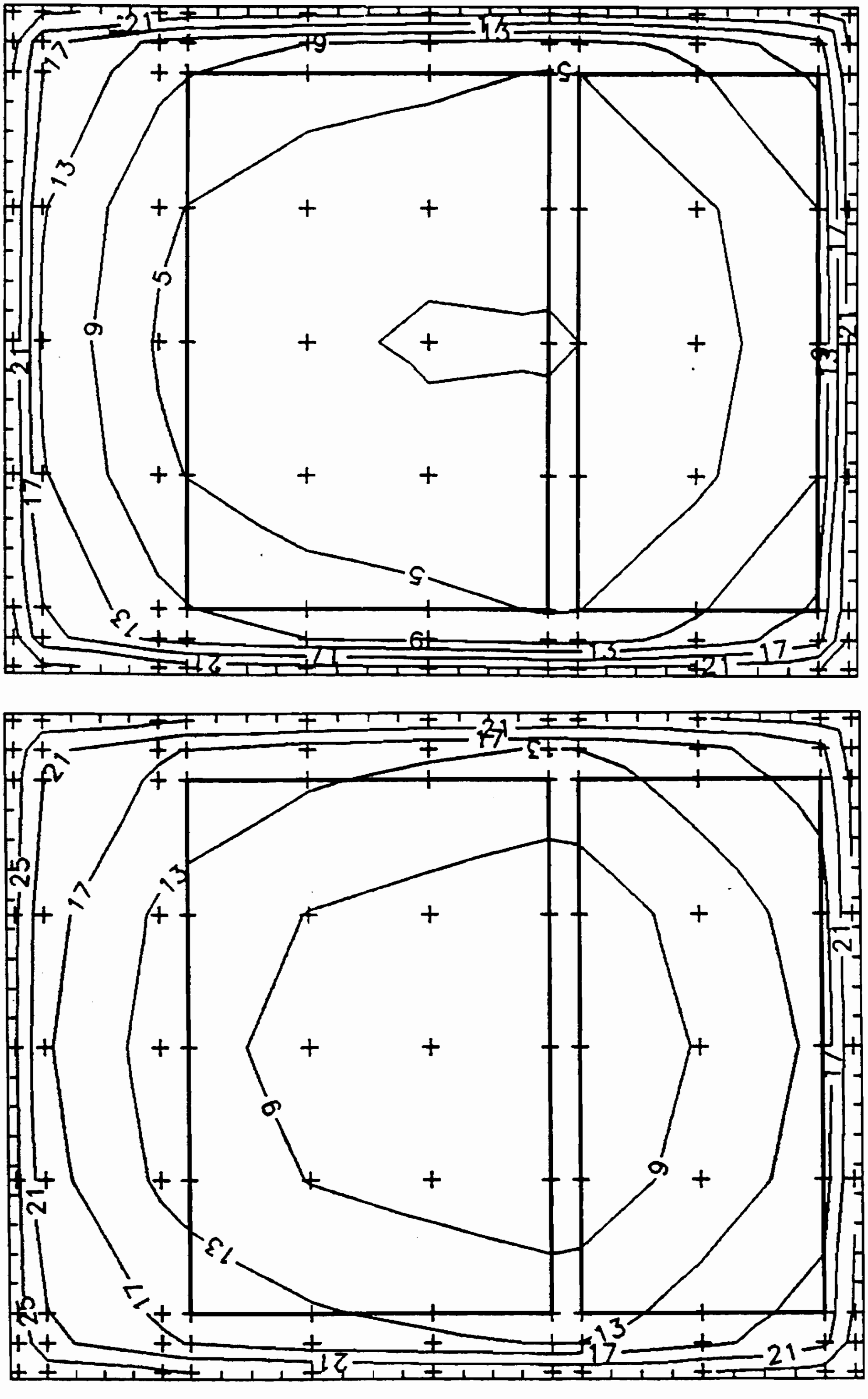

Figure 44. EQ container model at 12 hours with constant boundary conditions; icing method 2.

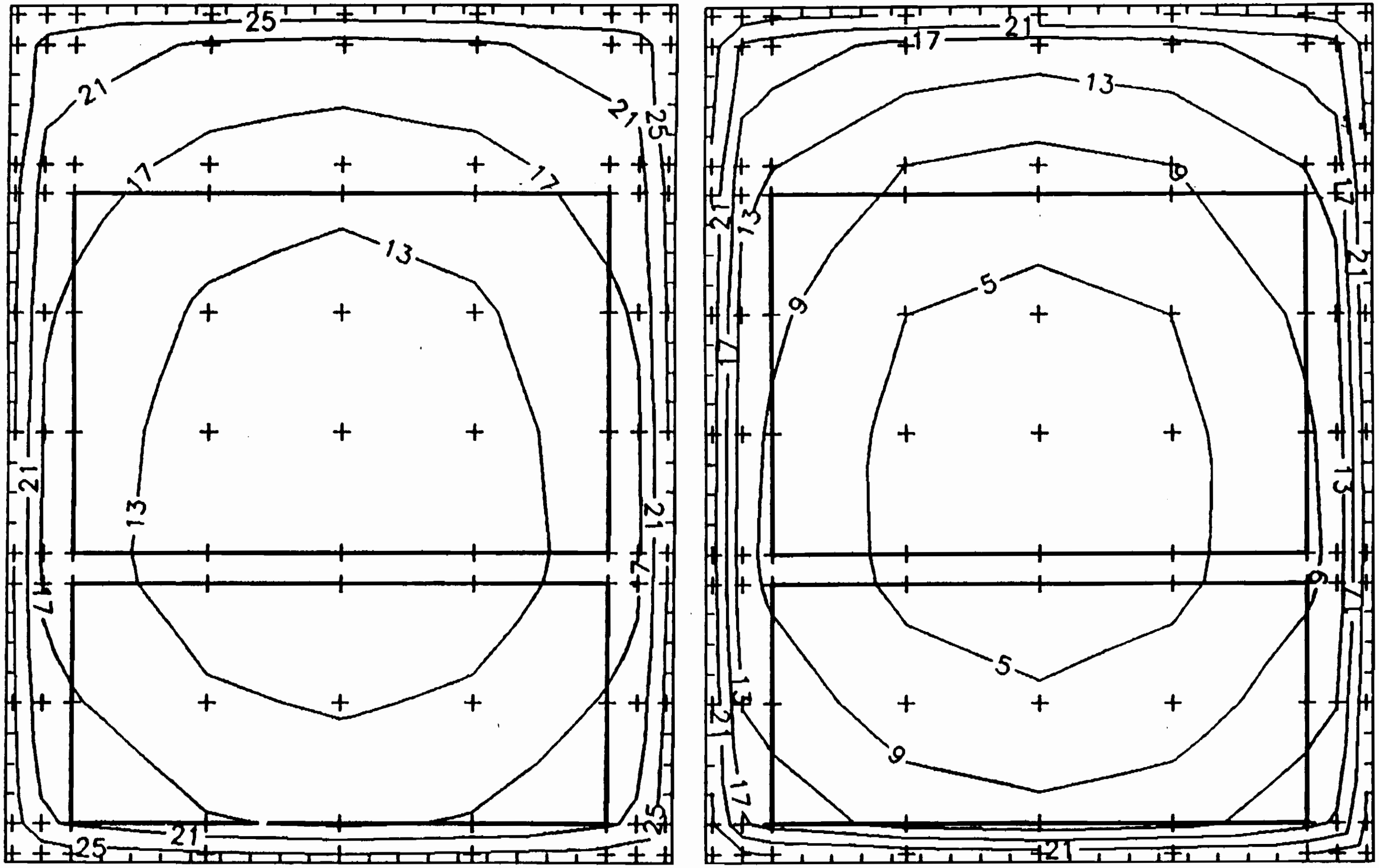

Figure 45. EQ container model at 18 hours with constant boundary conditions; icing method 2.

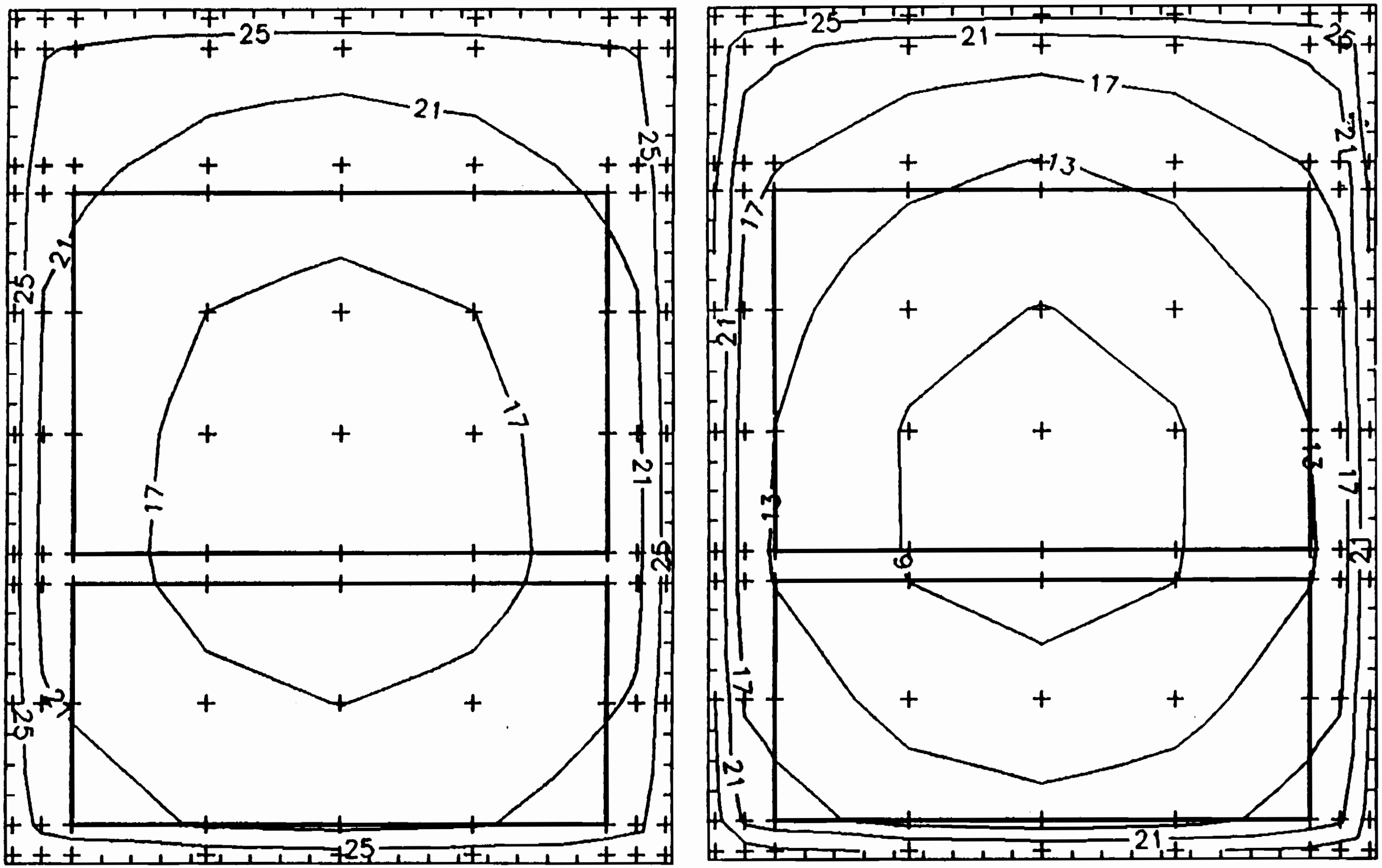

Figure 46. EQ container model at 30 hours with constant boundary conditions; icing method 2.

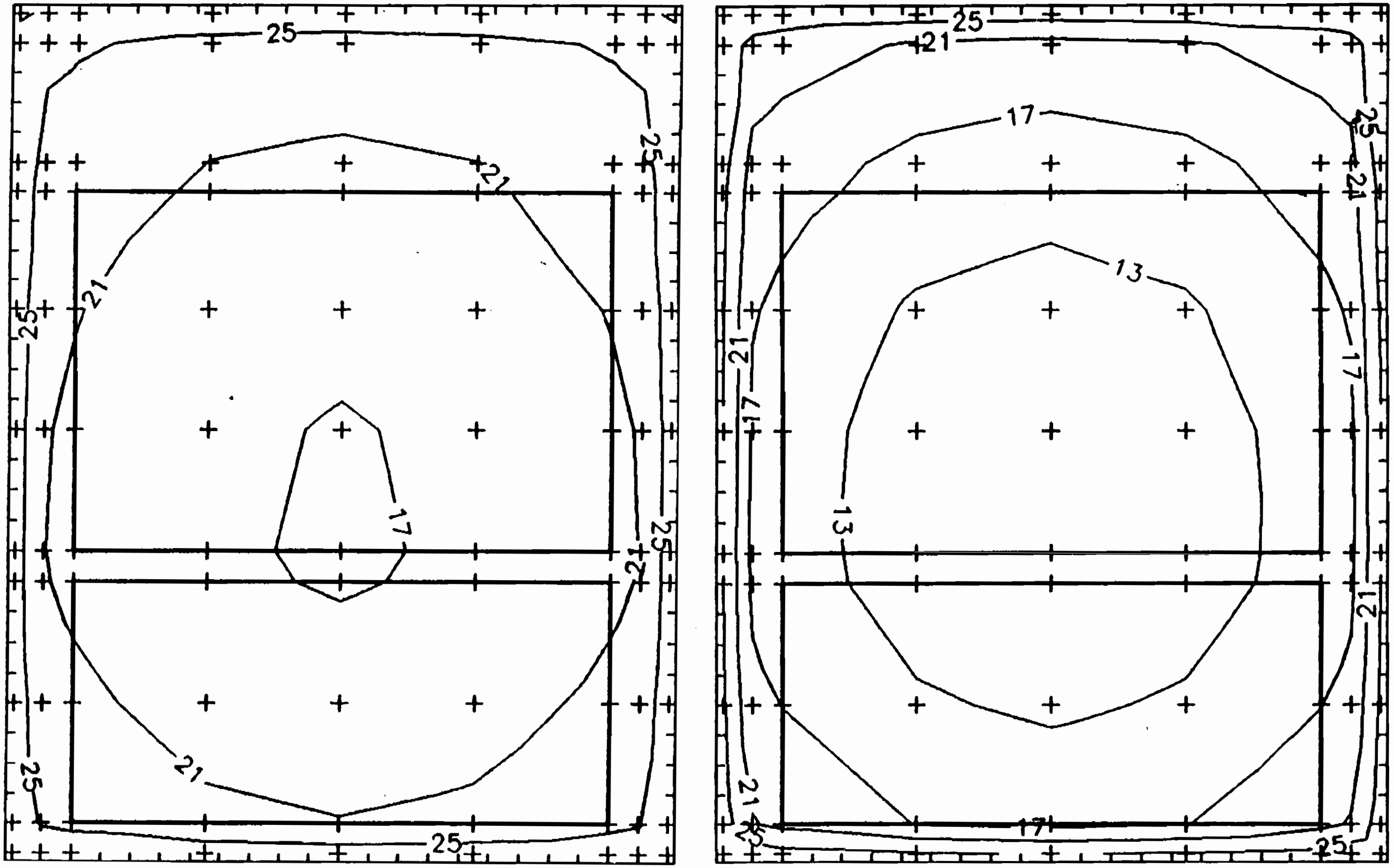

Figure 47. EQ container model at 36 hours with constant boundary conditions; icing method 2.

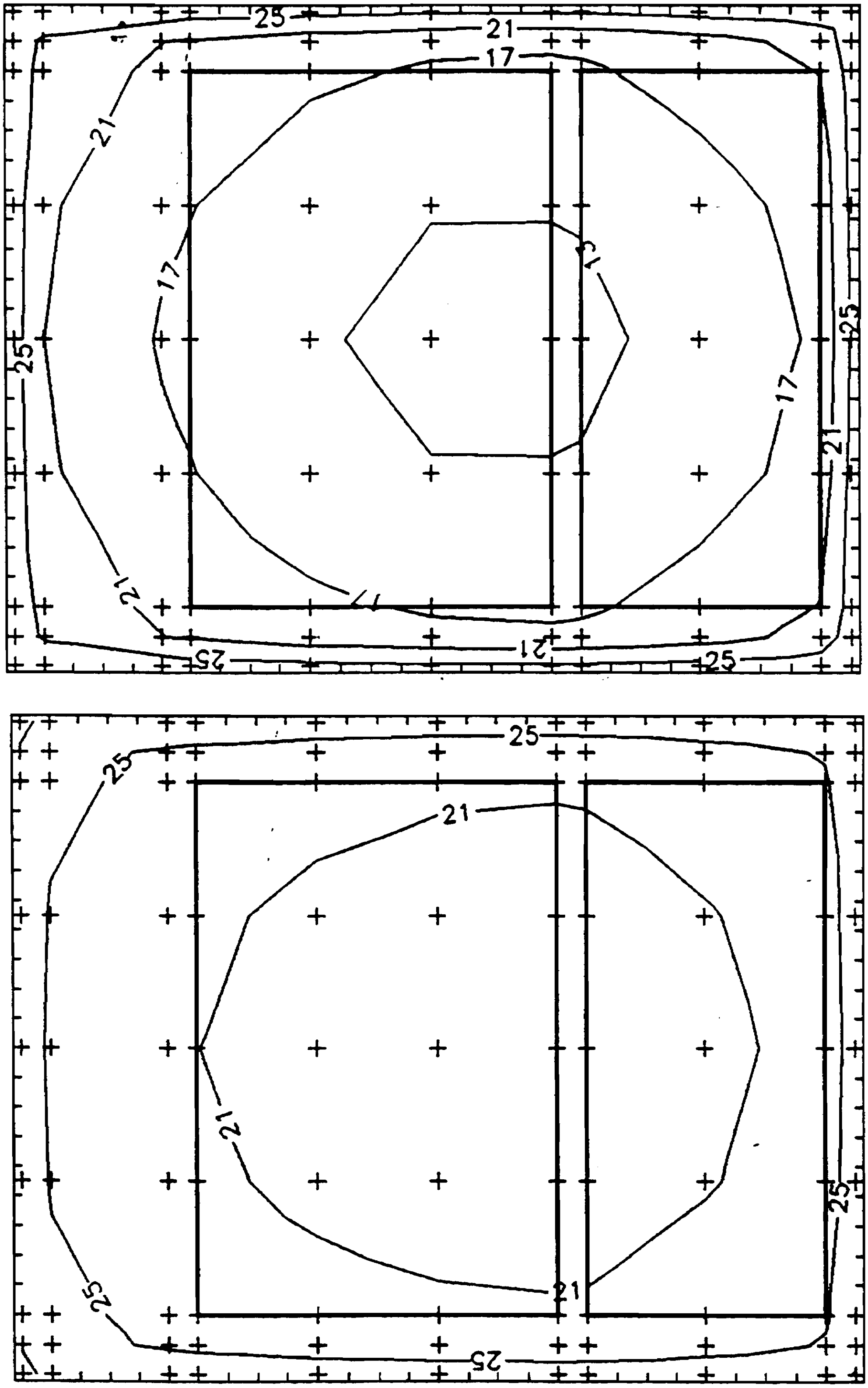

Figure 48. EQ container model at 42 hours with constant boundary conditions; icing method 2.

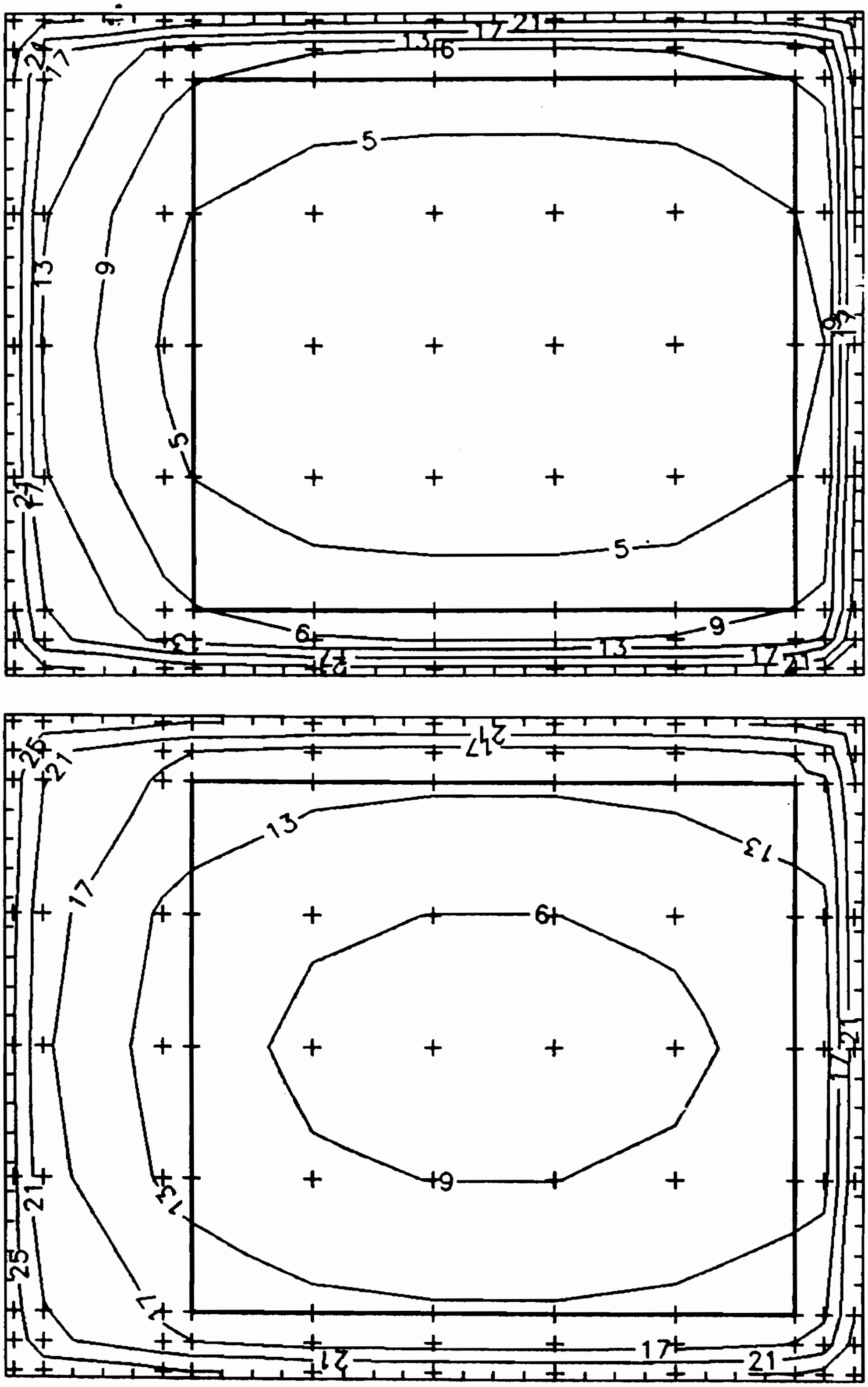

Figure 49. EQ container model at 12 hours with constant boundary conditions; icing method 3.

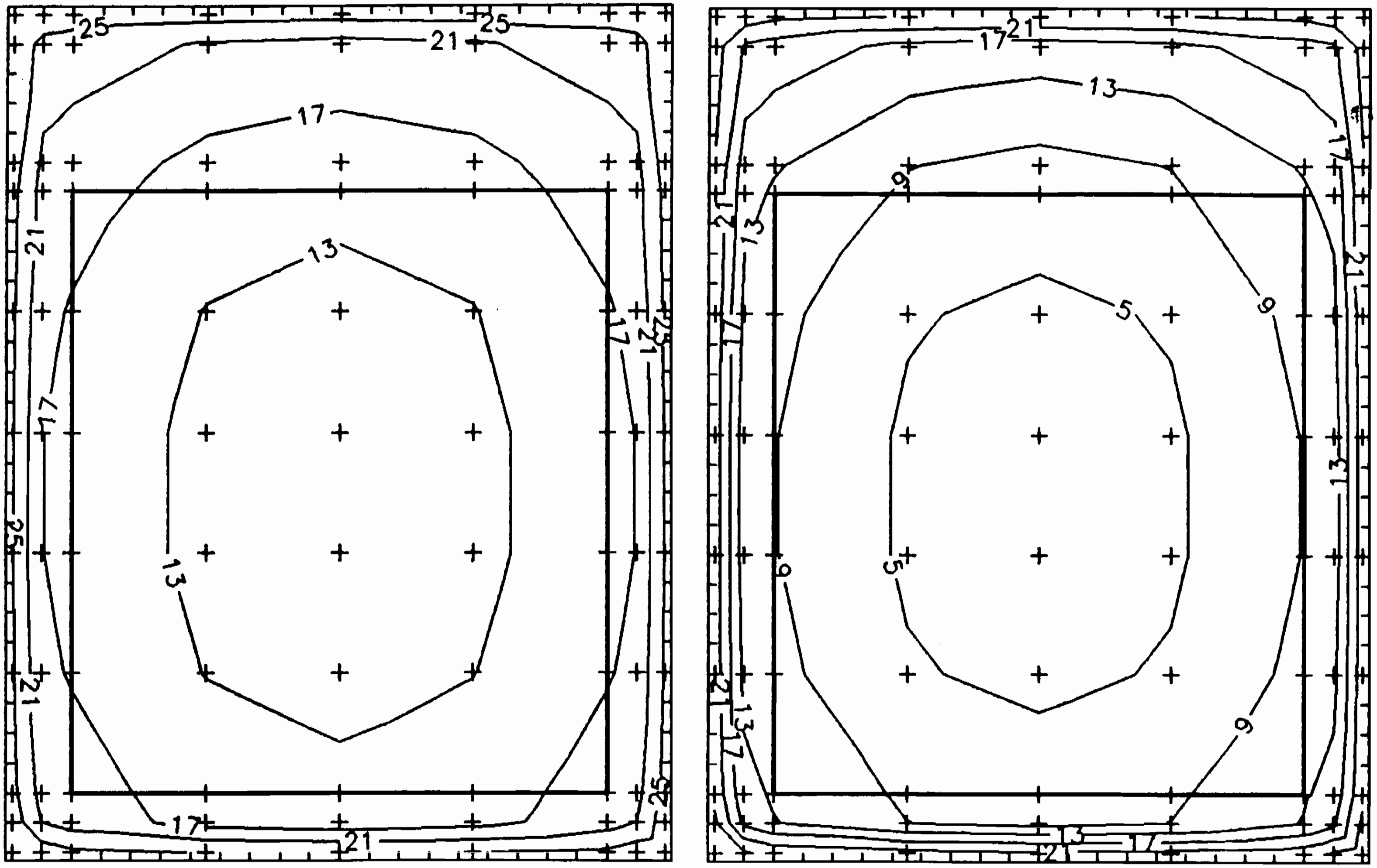

Figure 50. EQ container model at 18 hours with constant boundary conditions; icing method 3.

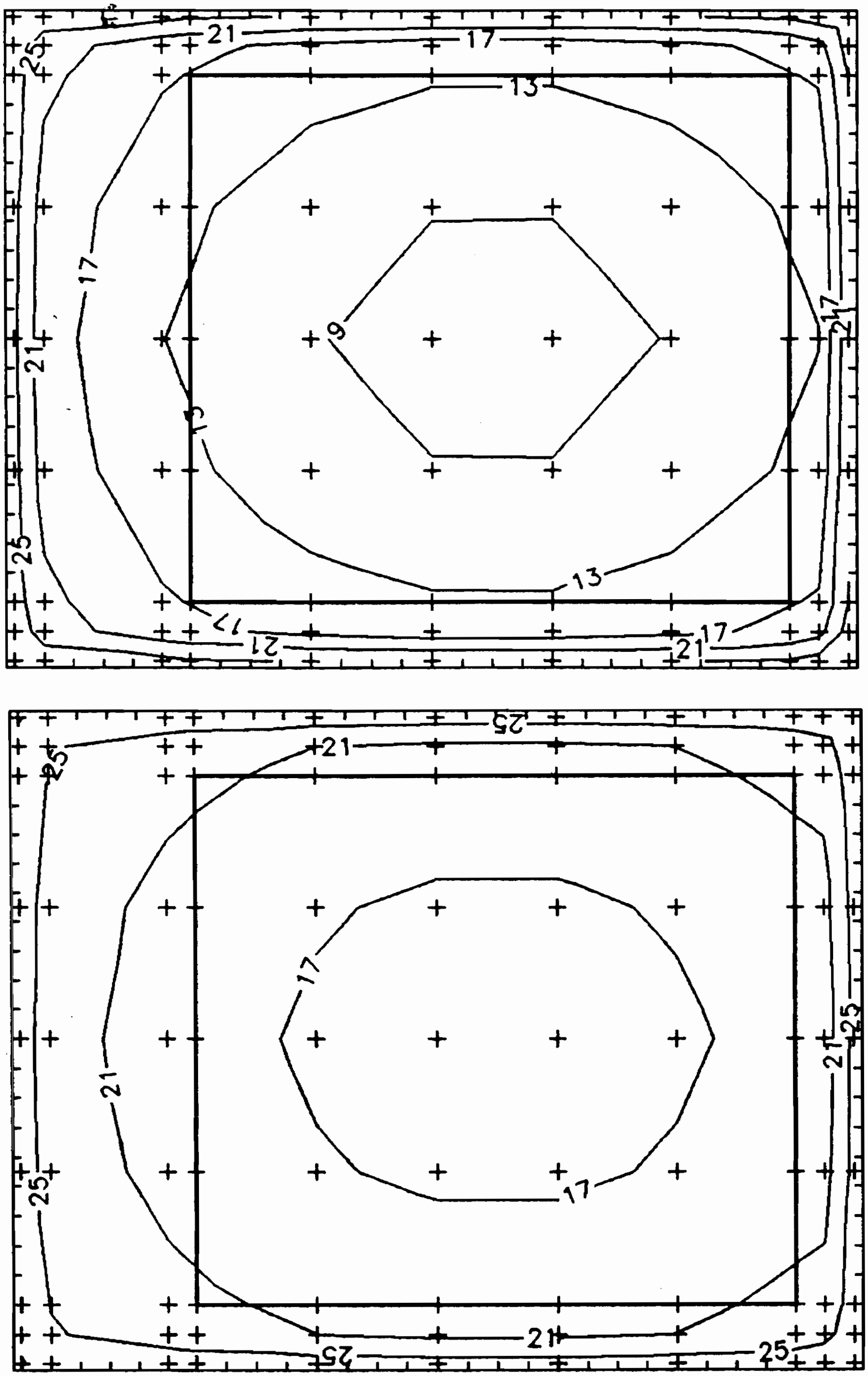

Figure 51. EQ container model at 30 hours with constant boundary conditions; icing method 3.

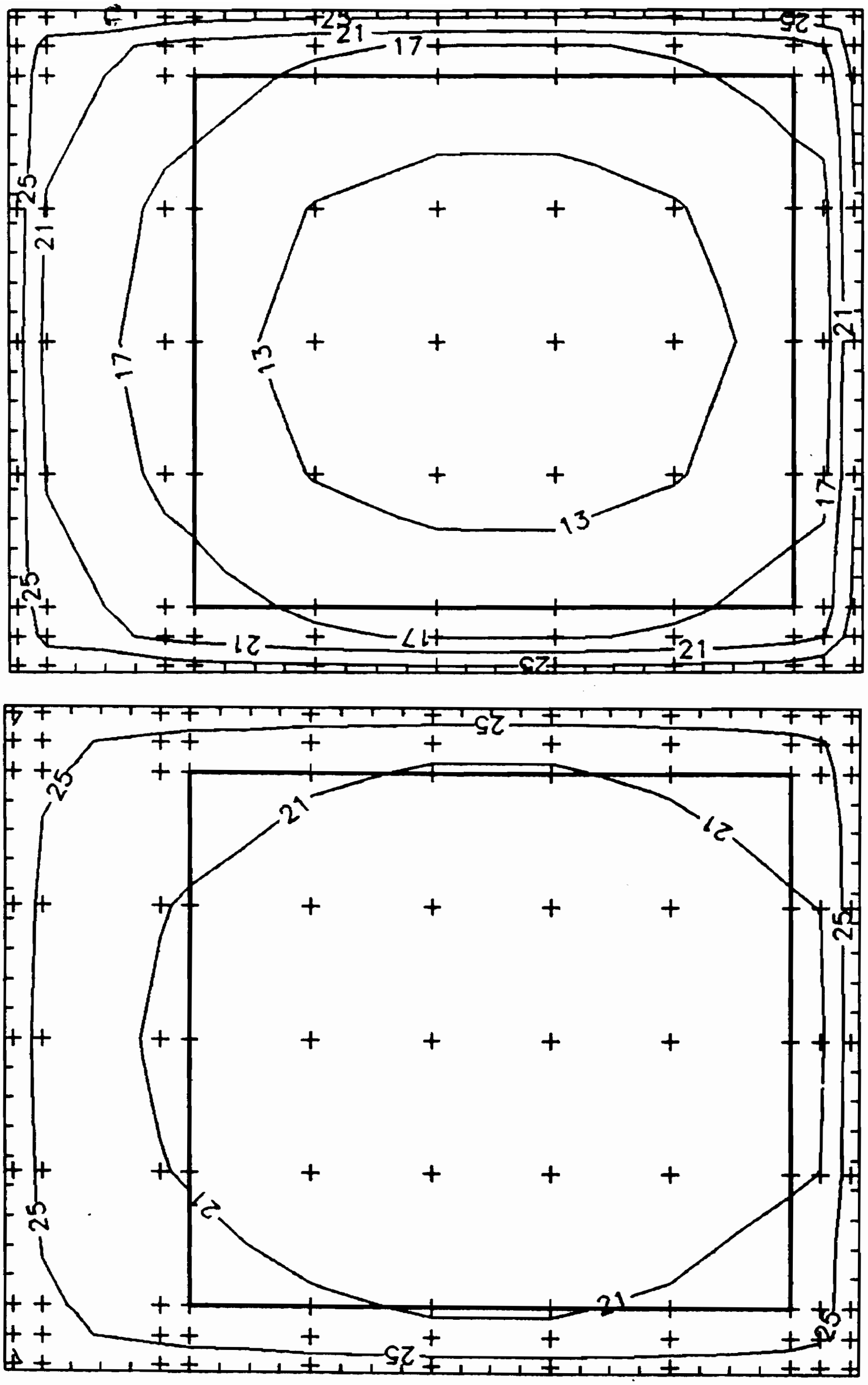

Figure 52. EQ container model at 36 hours with constant boundary conditions; icing method 3.

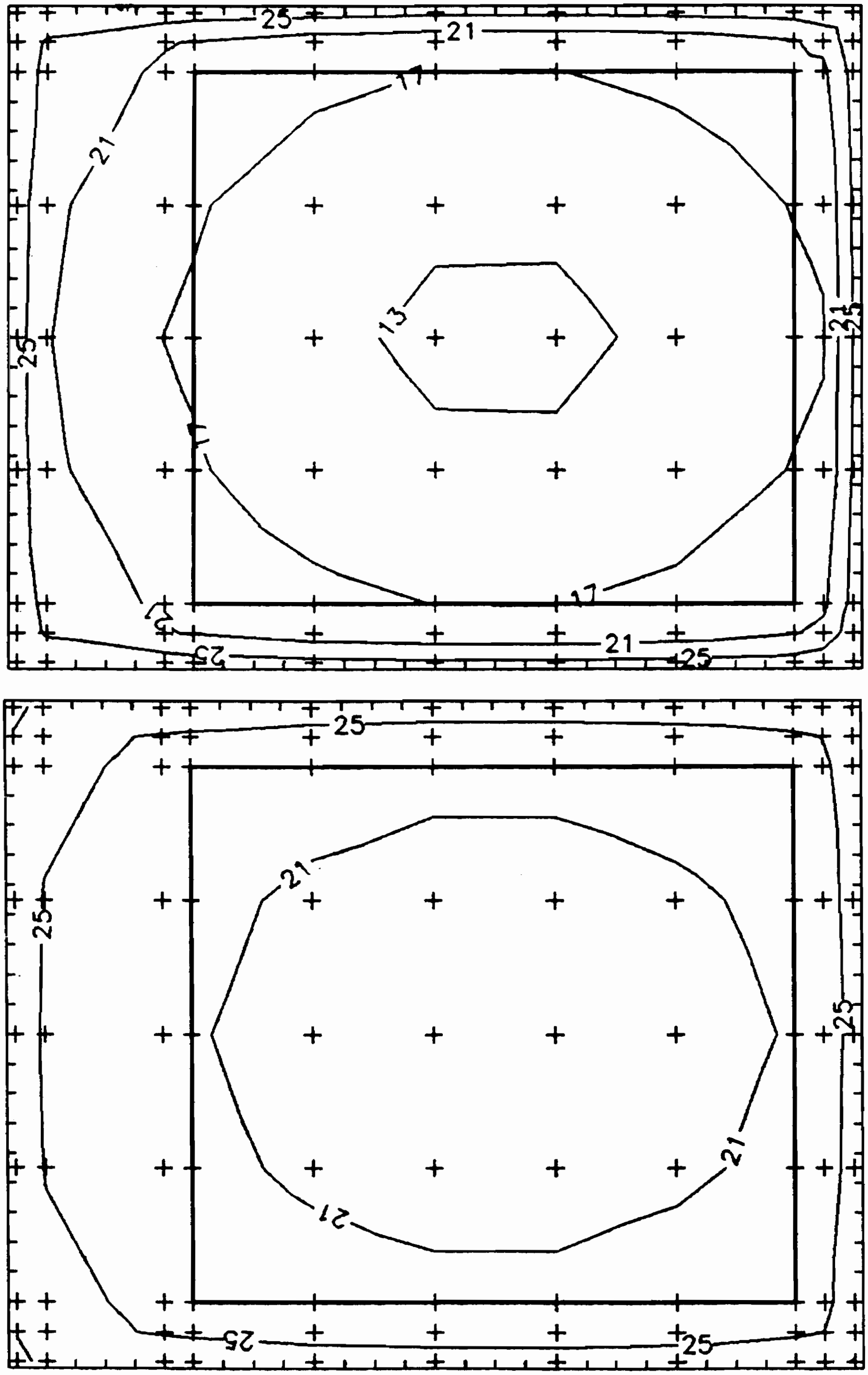

Figure 53. EQ container model at 42 hours with constant boundary conditions; icing method 3.

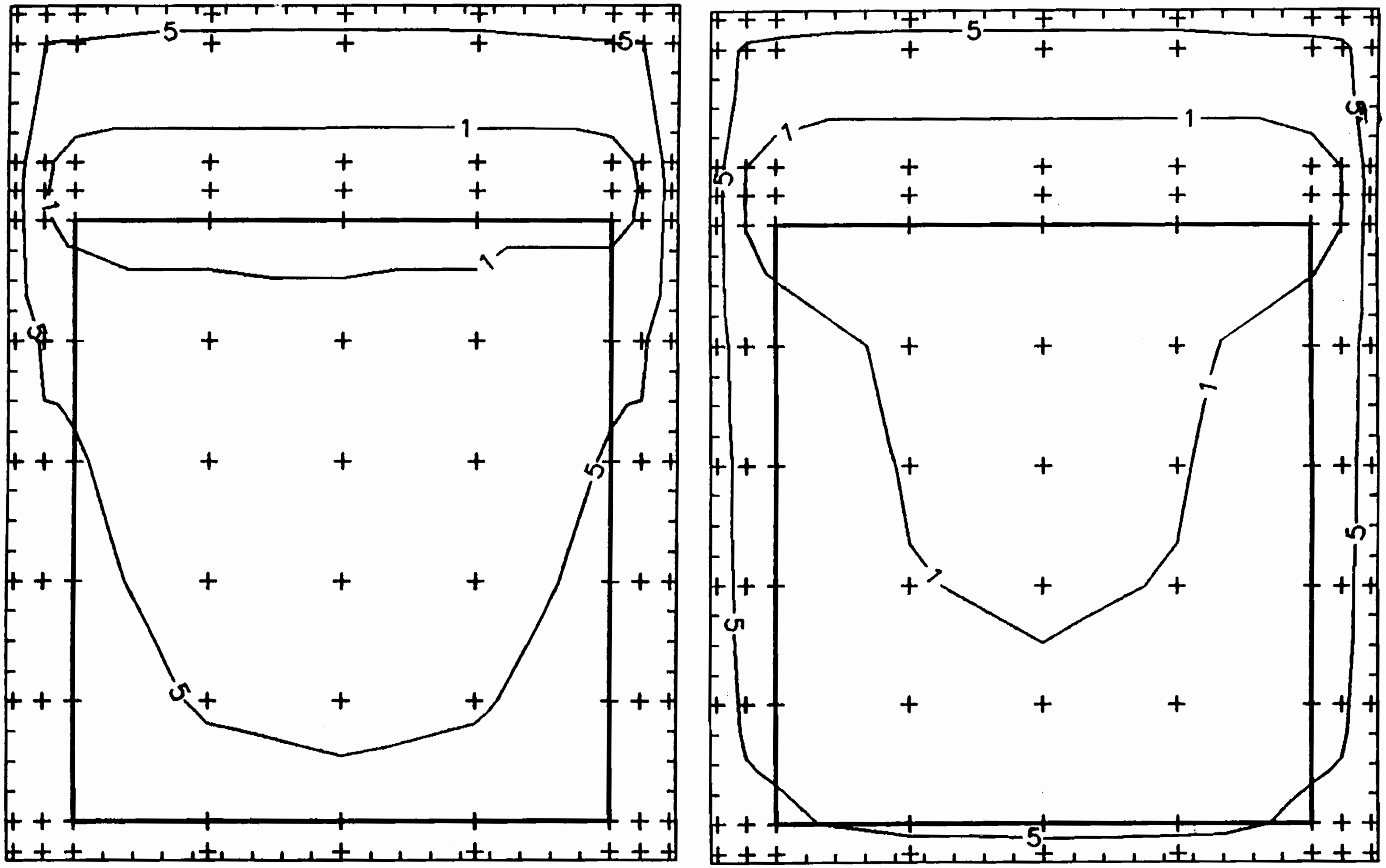

Figure 54. EQ container model at 12 hours for LA flight; icing method 1.

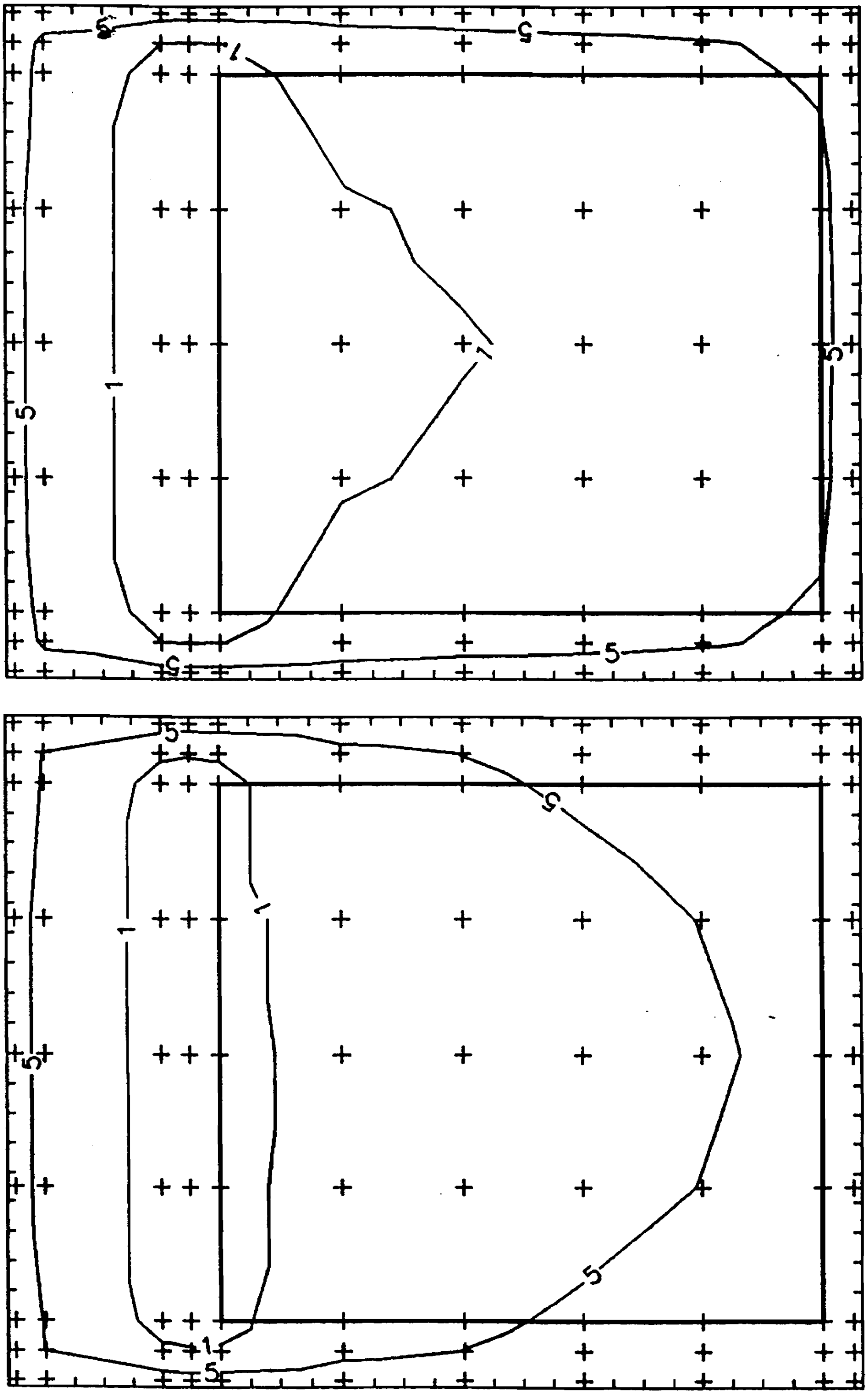

Figure 55. EQ container model at 18 hours for LA flight; icing method 1.

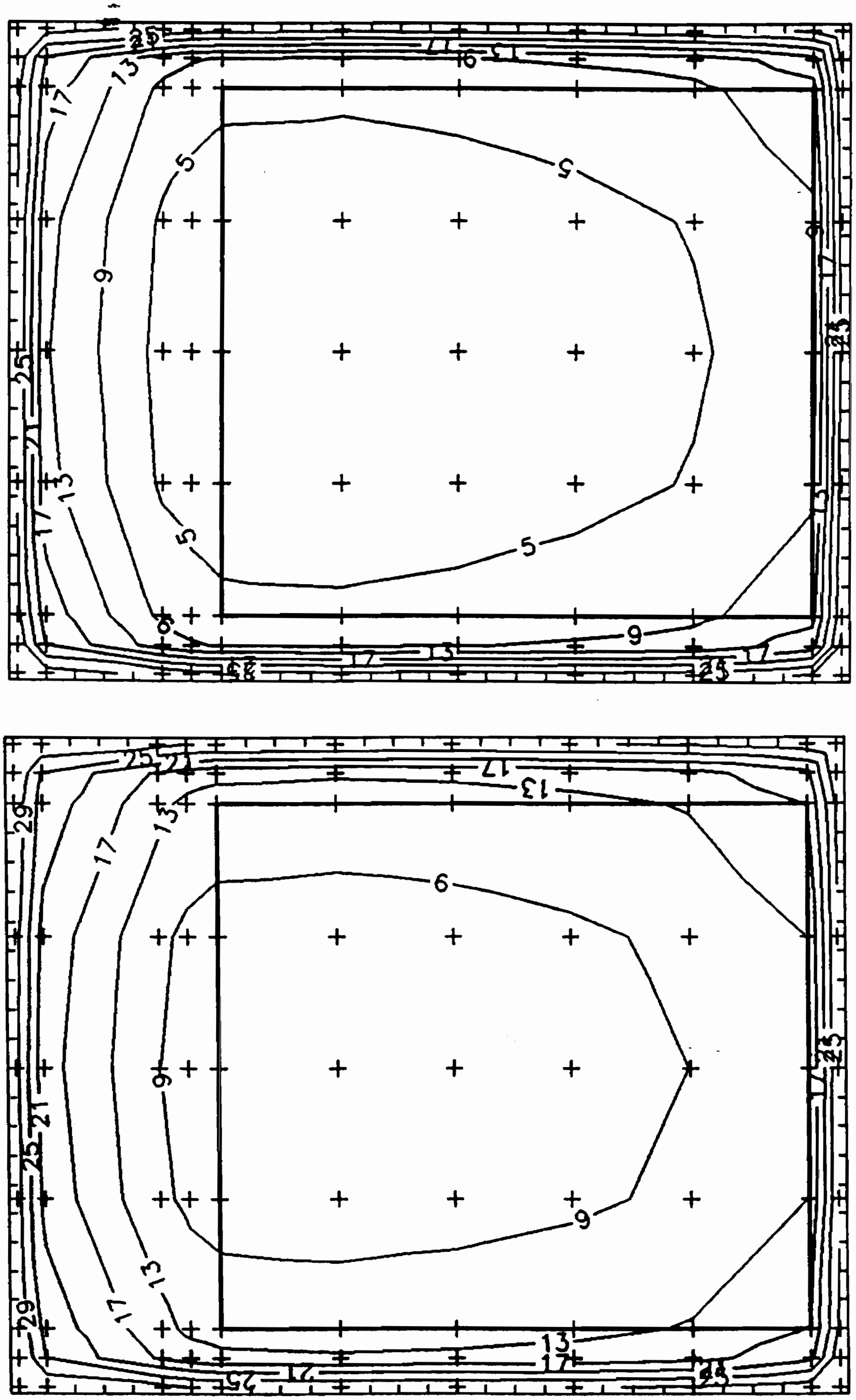

Figure 56. EQ container model at 30 hours for LA flight; icing method 1.

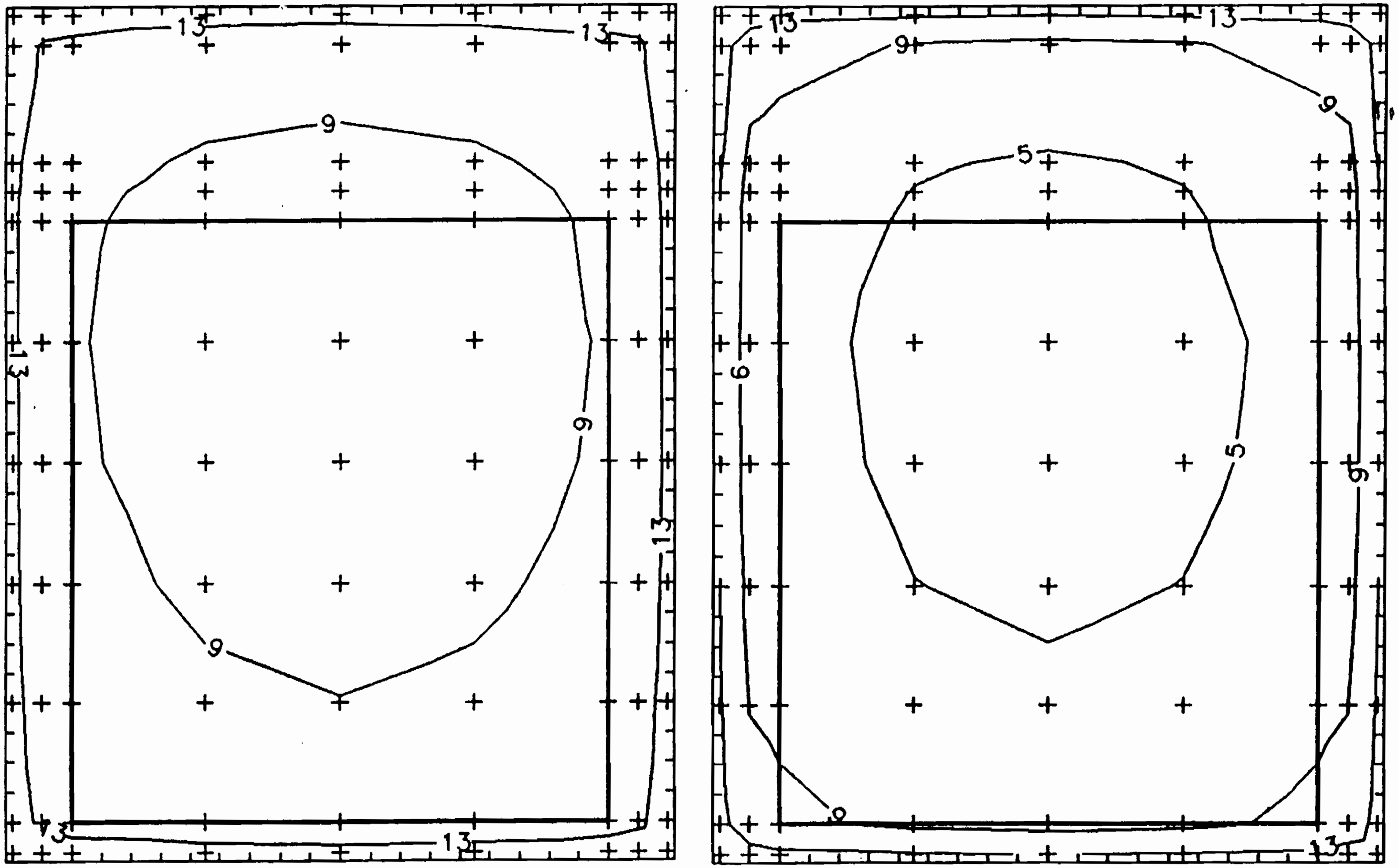

Figure 57. EQ container model at 36 hours for LA flight; icing method 1.

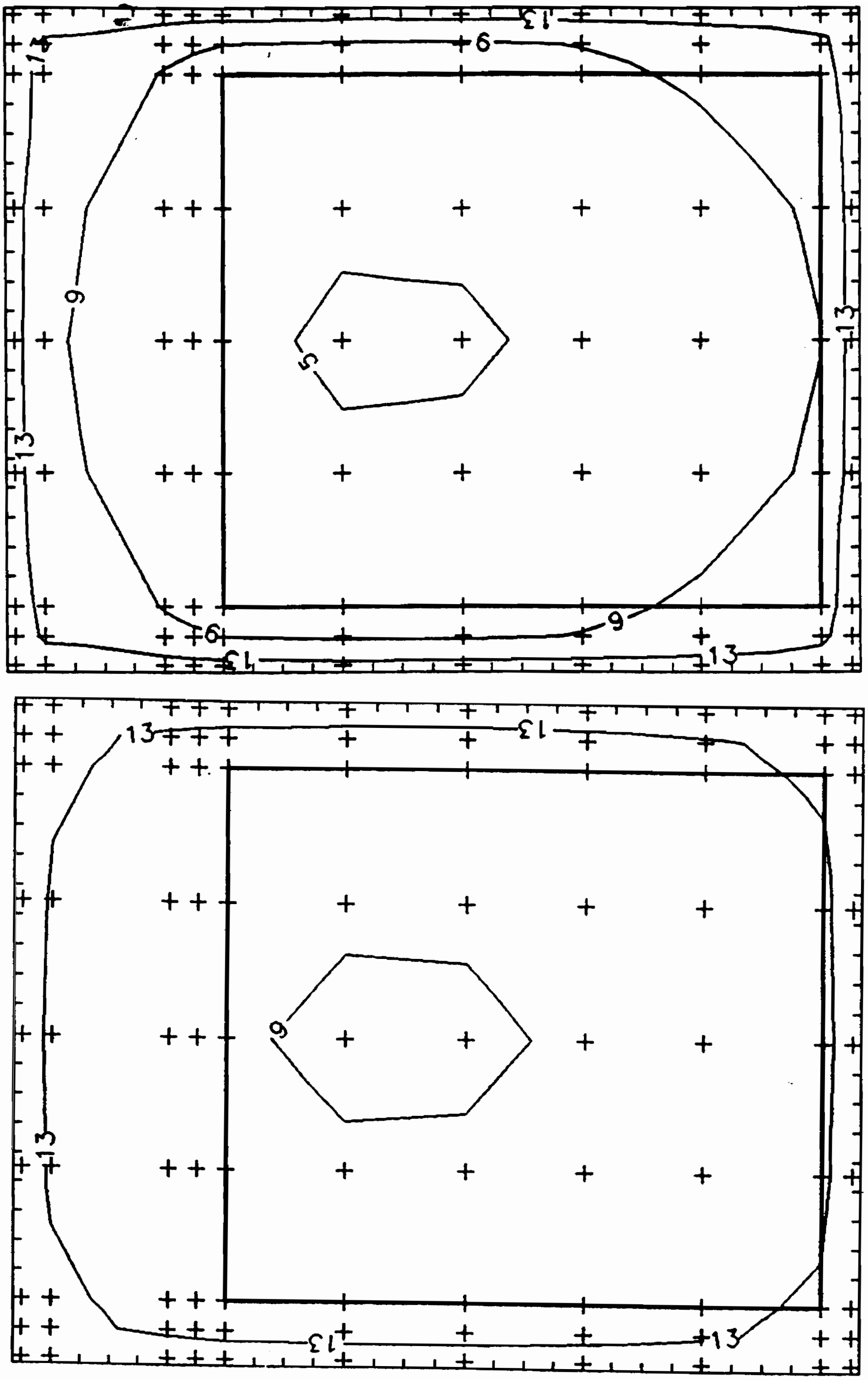

Figure 58. EQ container model at 42 hours for LA flight; icing method 1.

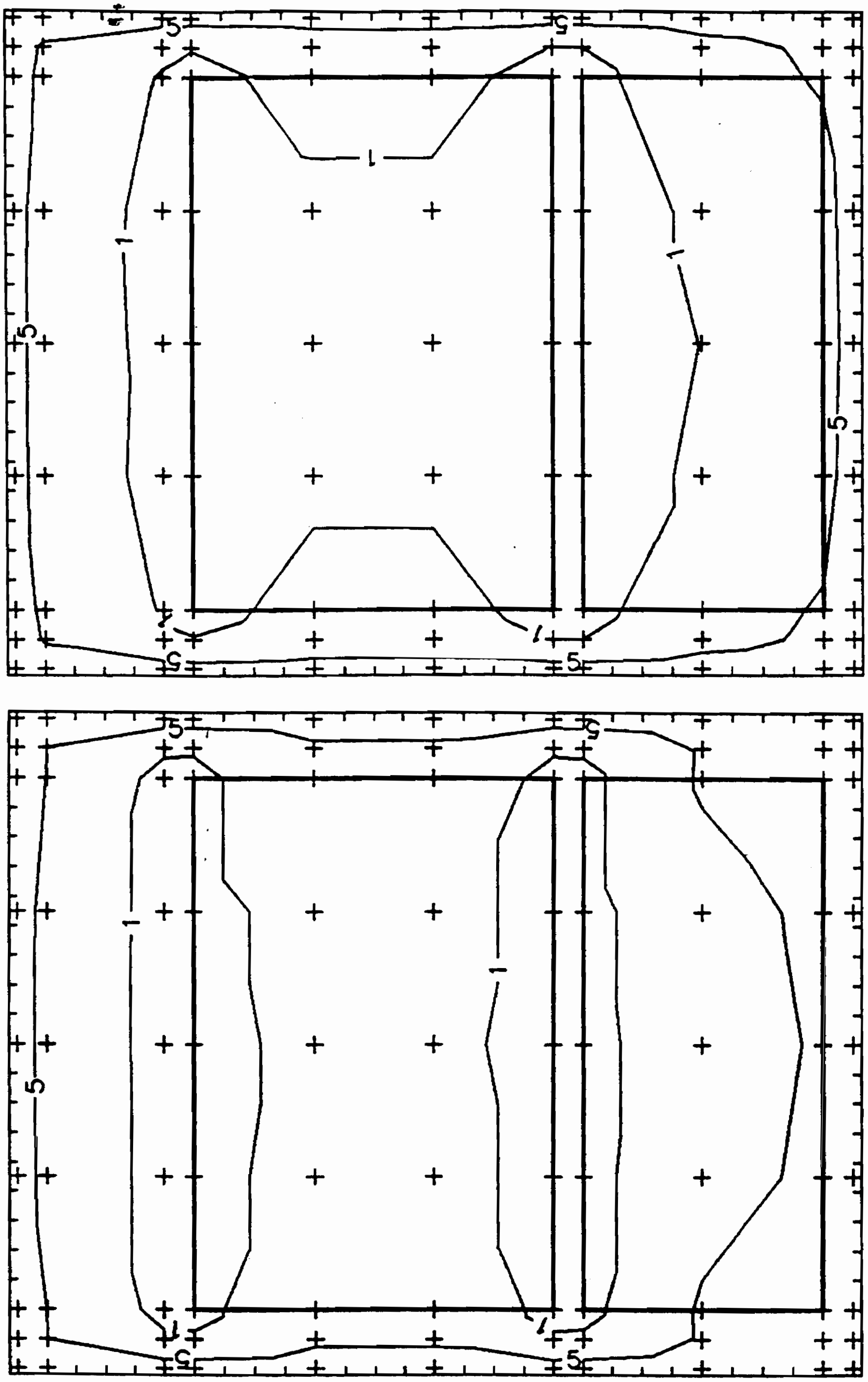

Figure 59. EQ container model at 12 hours for LA flight; icing method 2.

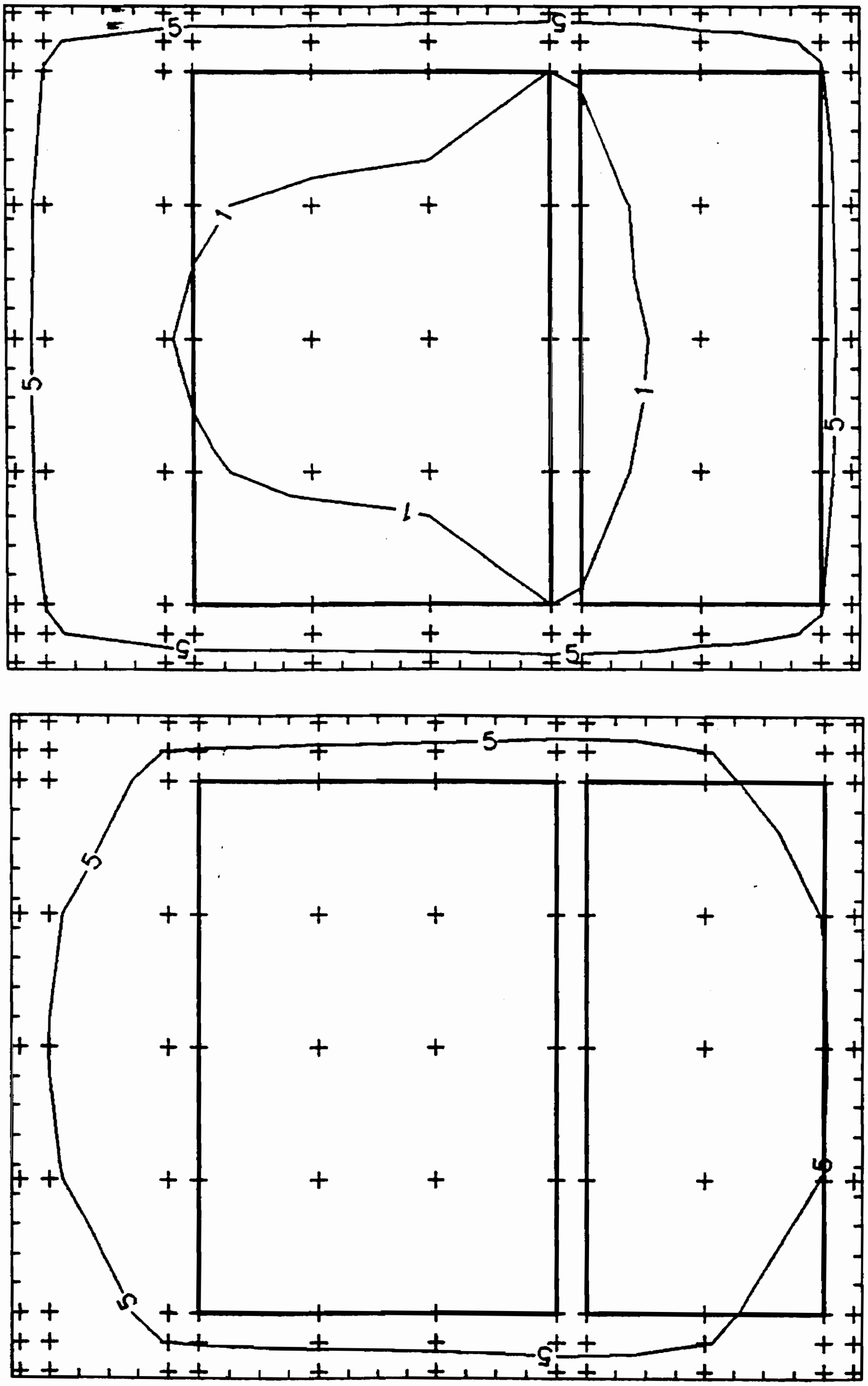

Figure 60. EQ container model at 18 hours for LA flight; Icing method 2.

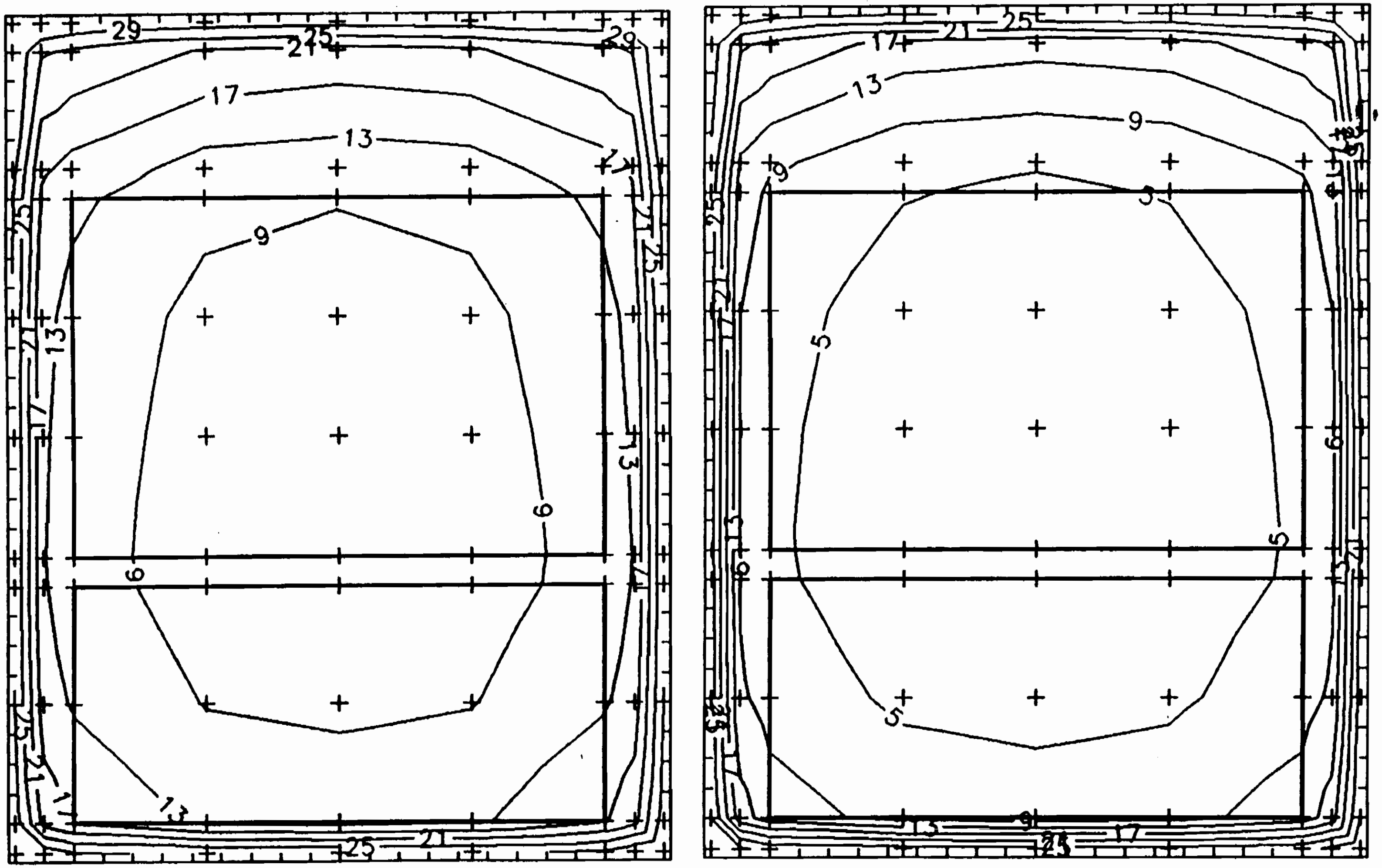

Figure 61. EQ container model at 30 hours for LA flight; icing method 2.

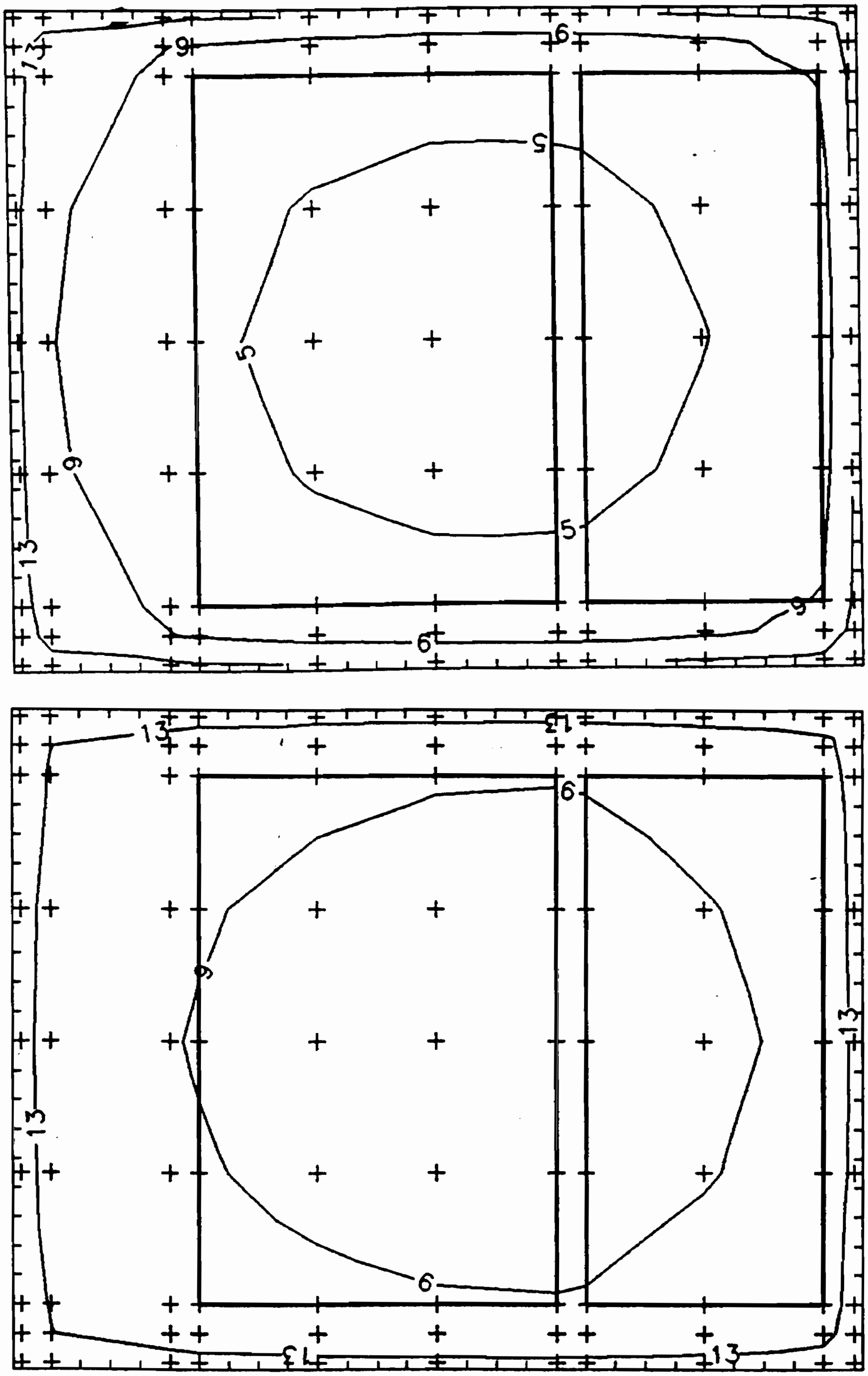

Figure 62. EQ container model at 36 hours for LA flight; icing method 2.

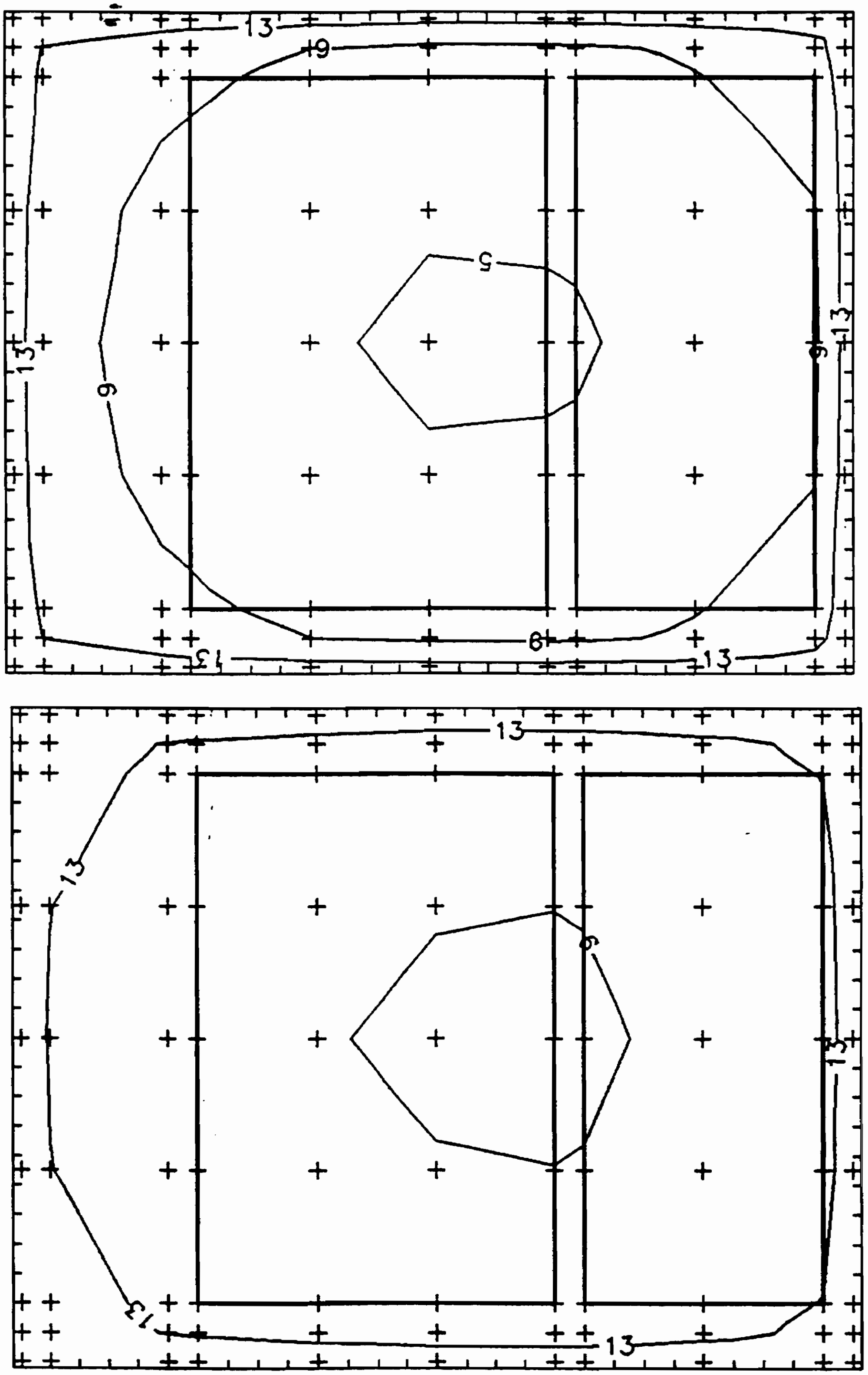

Figure 63. EQ container model at 42 hours for LA flight; icing method 2.

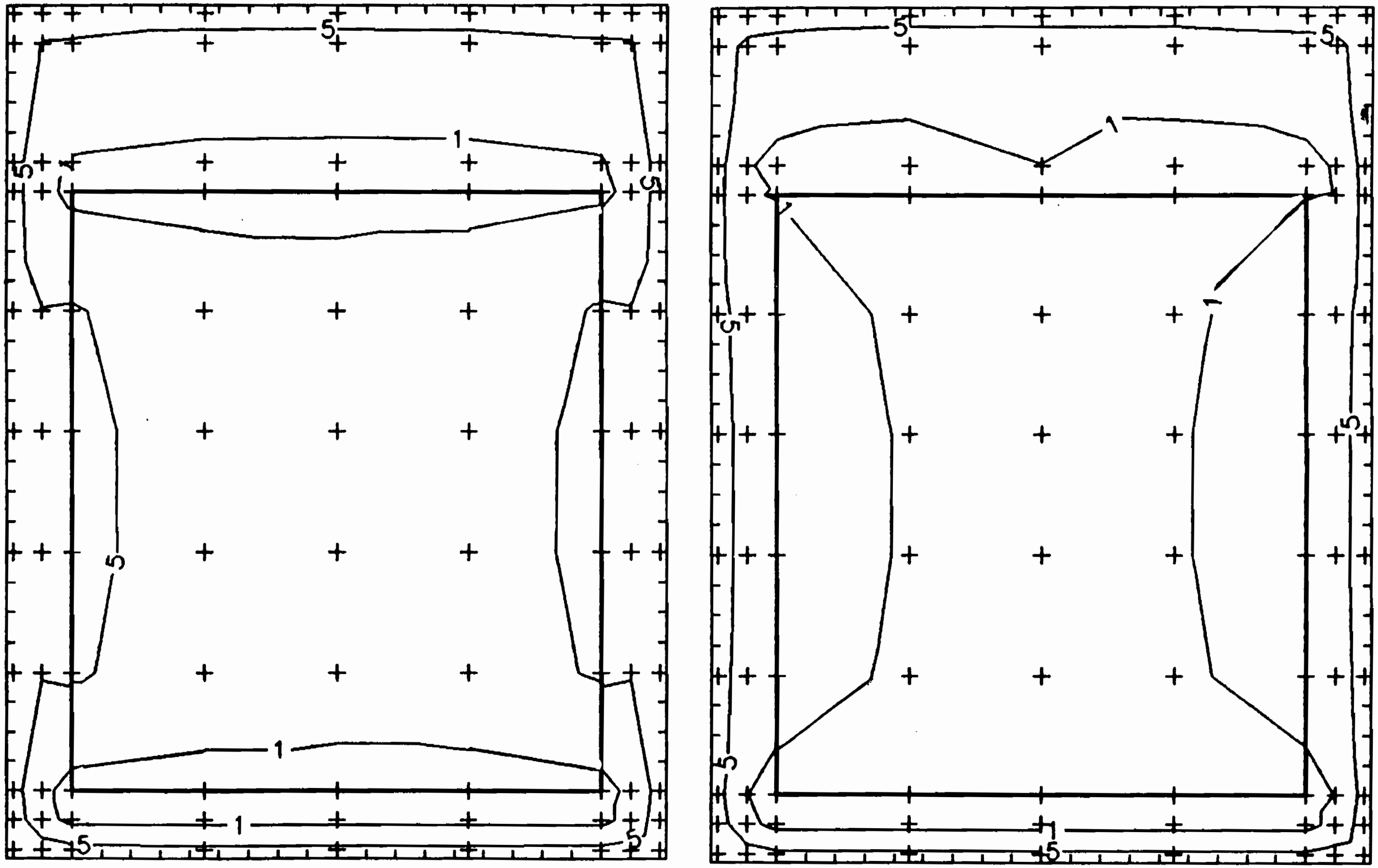

Figure 64. EQ container model at 12 hours for LA flight; icing method 3.

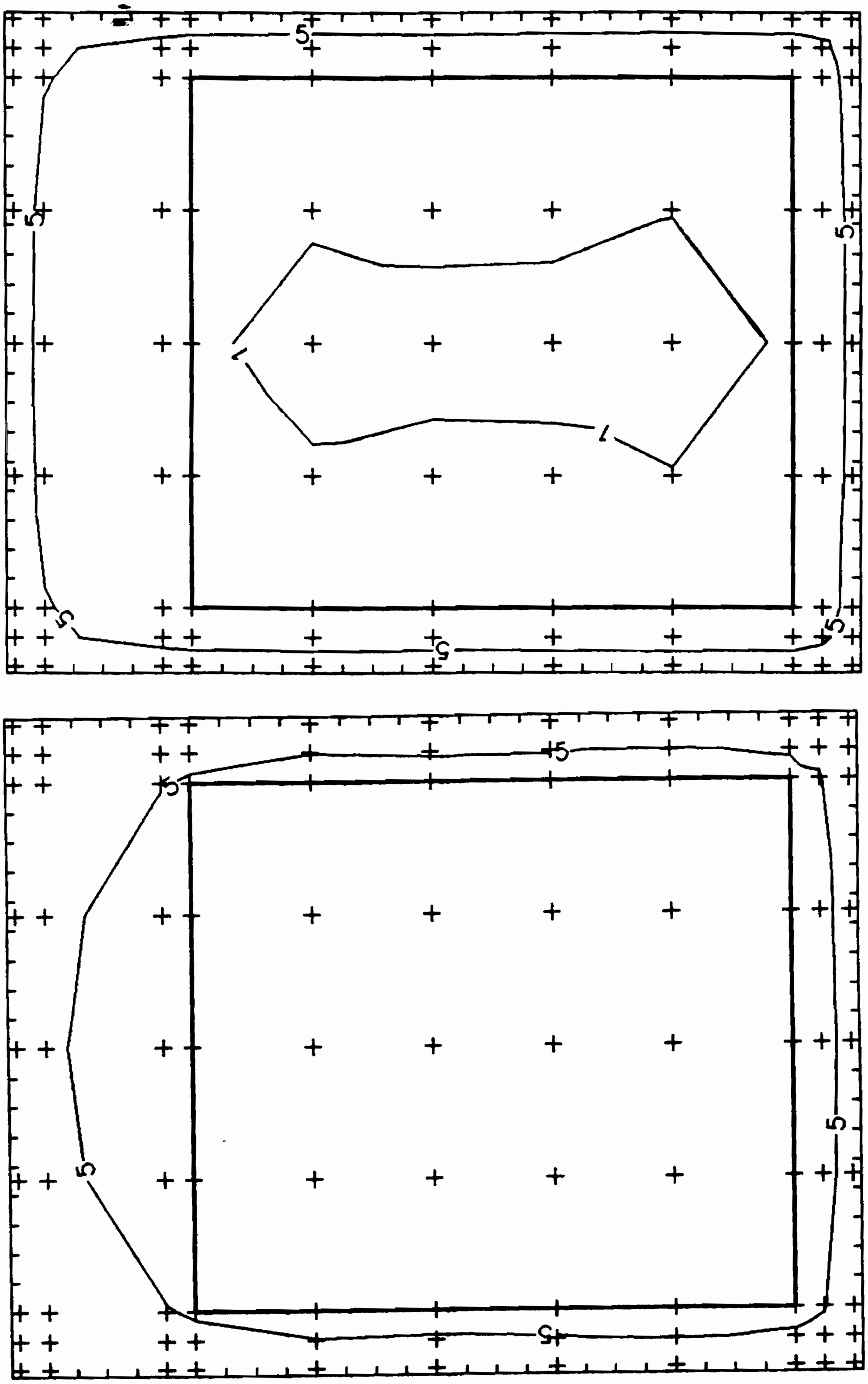

Figure 65. EQ container model at 18 hours for LA flight; icing method 3.

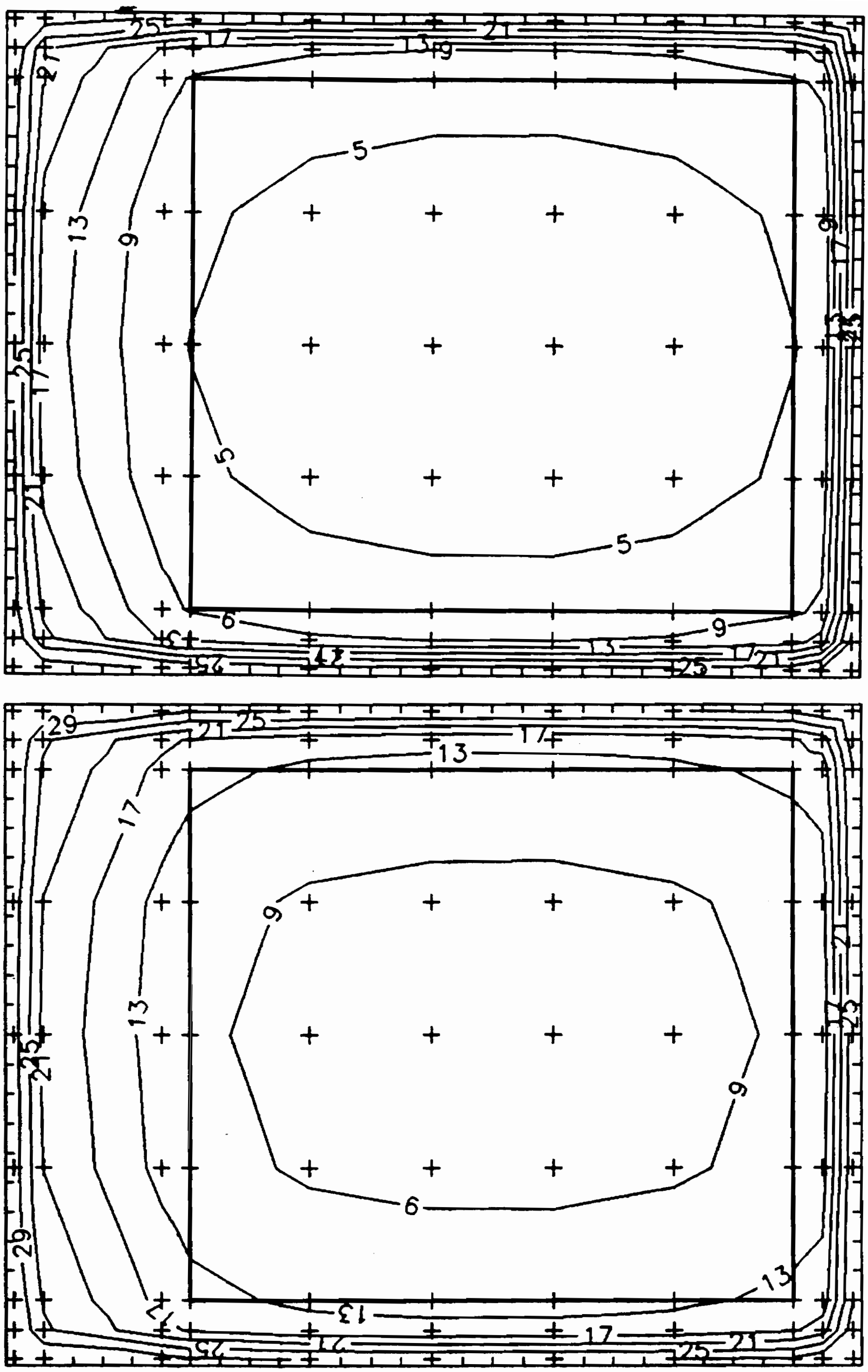

Figure 66. EQ container model at 30 hours for LA flight; icing method 3.

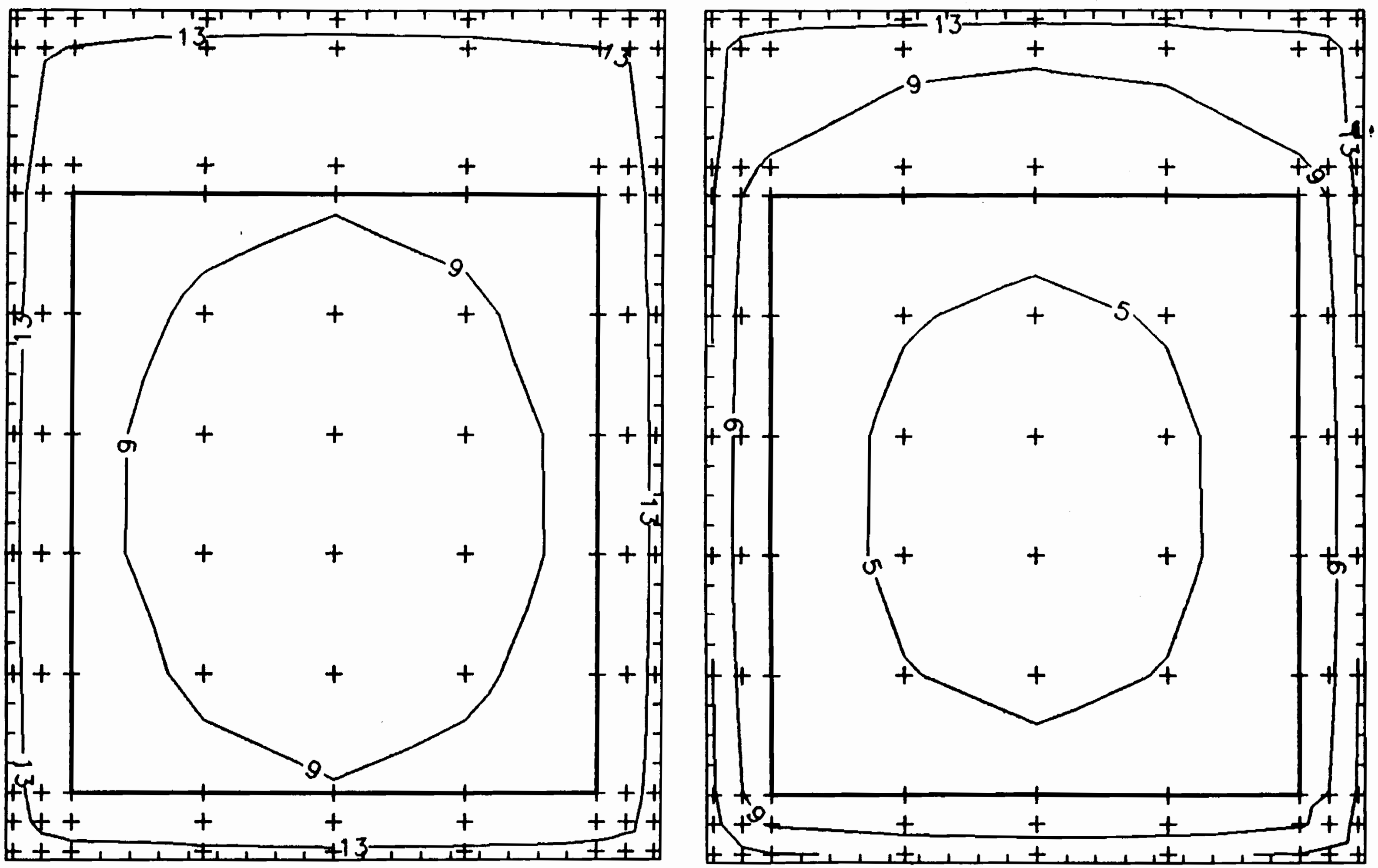

Figure 67. EQ container model at 36 hours for LA flight; icing method 3.

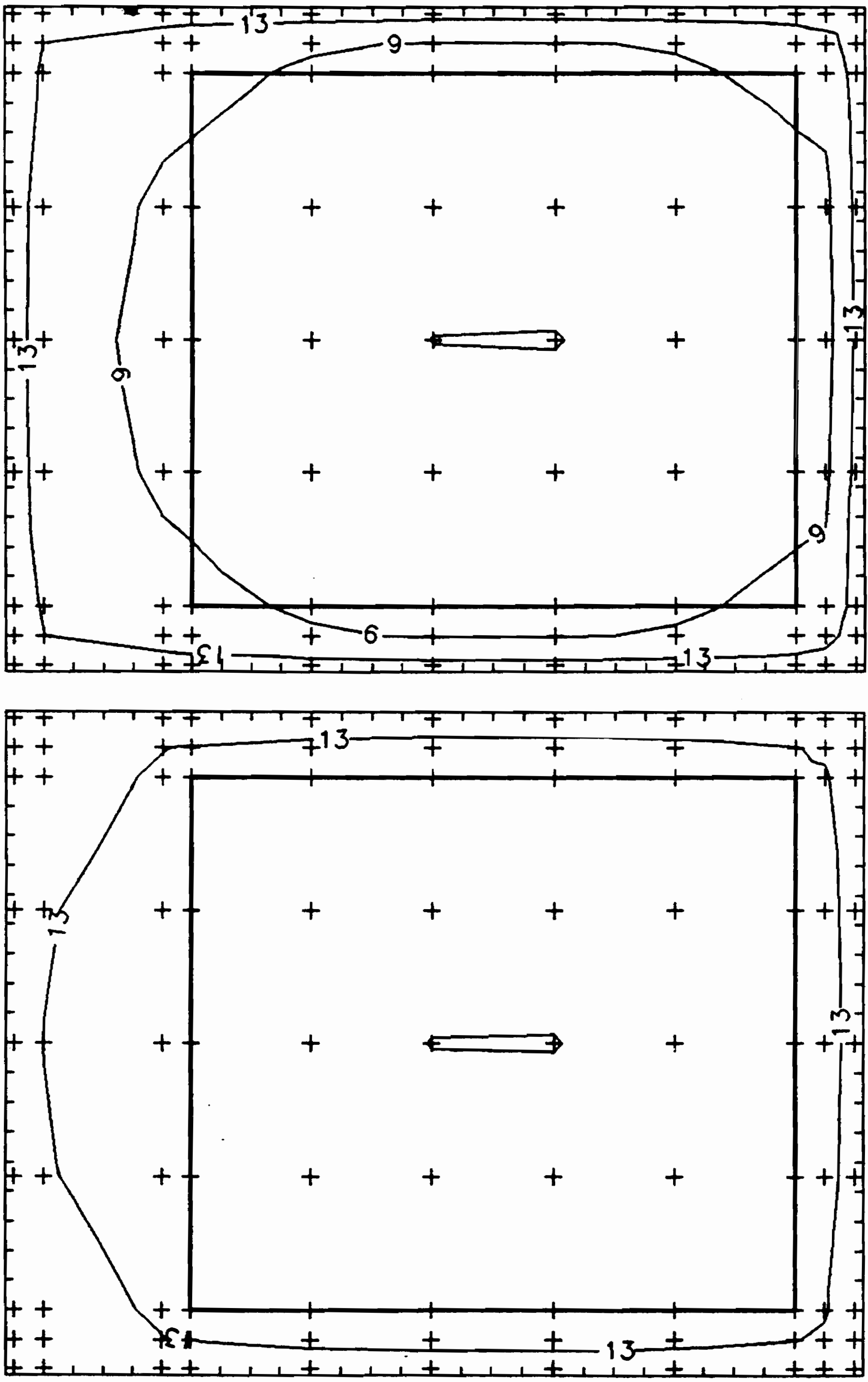

Figure 68. EQ container model at 42 hours for LA flight; icing method 3.

Vita

Lawrence J. Stringer was born in Falls Church, Virginia on 7 March, 1965. He grew up only a few miles from Washington, D.C. He attended Falls Church High School and there was active in drama, debate, swimming, and band. While in high school Larry decided he wanted to pursue an education in engineering.

In the fall of 1983 he entered Va Tech to pursue an undergraduate degree in agricultural engineering. Larry chose agricultural engineering as a major in order to "beat swords into plowshares." After finishing his undergraduate degree in 1987, he began work for the Agricultural Engineering department researching fresh seafood transportation and in 1988 began work on his Master's degree in that area of study. Upon completion of his Master's of Science degree Larry will be working for the federal government with the Food and Drug Administration. He will be in Chicago at the Center for Food Safety and Nutrition. Larry looks forward to living in Chicago and taking courses towards a Ph.D. in Food Engineering at Illinois Institute of Technology there.