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ABSTRACT

The lack of adequate temperature measurement is the major barrier to the development of more efficient and better quality food processing methods. The objective of the sonic temperature sensor for food processing project is to develop a prototype sensor system to noninvasively measure the interior temperature of particulate foods during processing. The development of the prototype sensor is a collaborative project with the National Food Processors Association. The project is based on the property of materials that involves a change in the temperature of a material having a corresponding change in the speed of sound. The approach for the sonic sensor system is to determine the speed of sound through particulate foods using a tomographic reconstruction process. This work has shown that the speed of sound accurately can be determined using tomographic reconstruction methods to an accuracy of $\pm 0.4\%$, which corresponds to a temperature uncertainty of $\pm 2^\circ\text{C}$.

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EXECUTIVE SUMMARY

The objective of the sonic temperature sensor for food processing project is to develop a prototype sonic sensor system to noninvasively measure the interior temperature of particulate foods during processing. The development of the sensor is based on a material property in which a change in the temperature of a material results in a corresponding change in the speed of sound as it moves through the material. The approach for the sonic sensor is to determine the speed of sound using a number of sensors and then to determine the temperature inside the particulate foods using a tomographic reconstruction process.

This project began in 1991 as an initial assessment of the speed of sound moving through foods as a function of temperature. This initial assessment was performed primarily with potatoes and indicated that there were discernible differences in the speed of sound passing through a potato as a function of temperature. Following the initial tests, a collaborative effort was begun with the National Food Processors Association (NFPA) to develop the technology.

An initial prototype was completed, and tests were performed with the sonic sensor system to assess the speed of sound as it passes through some materials. However, initial tests indicated that the original system had a number of problems that prevented accurate acquisition of the data needed for tomographic processing. Therefore, additional modeling of the process was performed and verification measurements were taken using a state-of-the-art commercial time of flight (TOF) sonic measurement system.

The objective of this report is to summarize the status of this series of theoretical calculations and experimental measurements that were performed using a measurement system that compensated for some of the problems associated with the initial prototype.

The theoretical evaluation of the sonic sensor process focused on the development of a two-dimensional map of sound speeds within a measurement can or pipe section. Following the development of this model using a 20×20 grid of transmitters and receivers, objects were placed in the model and the effects of these objects on the spatial resolution and noise effects were evaluated. In addition, a theoretical evaluation was performed on the effects of transducer size and refraction on spatial resolution.

TOF measurements were simulated for several different sizes of items in the measurement area. Refraction effects, transducer size effects, and measurement noise were included in the calculations. In all cases, the sound speed in the cylinders was 5% greater than that in the surrounding fluid. The TOF measurements were simulated for 45 transducers and for 30 transducers. For a 6-in. pipe with 45 transducers, the resolution threshold is approximately 1.2 in. For a 3-in. pipe for 45 and 30 transducers, the resolution values were calculated to be 0.45 and 0.6 in., respectively. The information implies that, for a 6-in. pipe, the spatial resolution of the sound-speed map estimation process is around 0.9 in. when 45 transducers are employed, and around 1.2 in. for 30 transducers.

This calculated spatial resolution would not meet the requirements stated by the NFPA of being able to resolve temperature variations within a pixel size of 0.25 in. Therefore, experimental measurements were performed to better assess the effects of numerous objects, noise, and refraction on spatial resolution.

Sonic transmission through canned corn, peas, and diced carrots was evaluated. The vegetables were placed in a rectangular plastic container with just enough water to fill the gaps. A few different transmitters were studied: four 0.5-in. transducers were used with center frequencies in the 1 to 15 MHz range; a 0.054-in. pinducer also was used. Measurements were acquired using a Matec Explorer 9000 ultrasonic instrument and two different pulsers: a square wave pulser and a spike pulser. The sound attenuation in db/in. was determined by comparing a water-filled container to the vegetable-filled container. The conclusions are as follows:

- Corn and peas produce significantly more attenuation compared to the diced carrots, and it may be difficult to make measurements at frequencies above 5 MHz.
- In all cases, transit time was less through vegetables than through water, indicating the higher velocity of the subject vegetables.
- The vegetables generally act as a low-pass filter (more than 3 MHz), which means that lower frequencies are not significantly attenuated by the food materials.
- Pinducers do not have adequate power to penetrate 2.65 in. of dense food particles, which indicates that the use of point source transmitters may be ineffective.
- The square wave pulser provides far better penetration than a spike pulser, which indicates that narrow band transducers and narrow band excitation is preferable.

Transmission of an ultrasonic pulse is detectable through canned corn and peas when the transmitting and receiving transducers have the same axis. However, the attenuation is probably too high for the vegetables to be inspected using a pipe array sensor if off-axis sensors are used to measure the attenuation. In the pipe array sensor, most TOF measurements will be made between off-axis transducer pairs. The ultrasonic signal emitted in the direction of an off-axis transducer is generally weaker than in the on-axis direction and flows weaker as the off-axis angle increases. Corn and peas are both surrounded by a semi-rigid shell, which might explain the difference in the attenuation when compared with diced carrots.

In some experiments with canned corn and peas, the transmitted ultrasonic pulse appears delayed by the vegetables—that is, sound speed in water appears greater than that propagating through the vegetables. The difference in the sound speed suggests that the transmitted ultrasonic signal propagates around the vegetable particles by scattering or diffraction or both. The signal penetrating the vegetables apparently suffers so much

attenuation that it becomes undetectable. The scattered and diffracted signals are of no use for sound-speed destination because the interior of the food particles are not sampled.

Ultrasonic pulses propagating through corn, peas, and diced carrots appear to undergo low-pass filtering. It is not known whether the filtering is caused by particle size or material properties. If the filtering is caused by material properties, it would be appropriate to use the lowest frequency possible with adequate measurement accuracy. The tradeoff between penetration and measurement accuracy is a design consideration that will have to be addressed for each different geometry and food type.

This work has shown that sound speed can be determined, using a 45-transducer pipe array, to an accuracy of approximately $\pm 0.4\%$, corresponding to a temperature uncertainty of approximately $\pm 2^\circ\text{C}$. The accuracy is achieved in the central region of the pipe. The size of the central region is determined by the transducer beam width. An analysis that was performed of the estimation process indicates that TOF measurement noise will not be a limiting factor. The analytical data suggest that if the resolution could be improved to 0.25 in., the temperature measurement would be sufficiently accurate for NFPA requirements.

Variations in the material properties of the processed foods may present problems for the implementation of this temperature measurement technique. If the sound speed in a certain type of food varies significantly between samples at canning temperatures ($> 120^\circ\text{C}$), then it may be difficult to inspect that food type using this technology. It has been noticed during this work that the sound speed in potato samples varies by $\pm 1.2\%$ at room temperature. This error is three times larger than the estimation error noted above. However, some initial work suggests that at canning temperatures, variations between the different food types becomes negligible.

Both the theoretical and actual measurements indicate that temperature estimation accuracy should be within the requirements of the NFPA. However, the spatial resolution requirement has not been met. Measurement results on foods suggest that transducer improvements that would produce a narrow band that results in more power than those currently in use is required. In addition, the results indicate that the speed of sound as it moves through processed foods varies significantly at the temperatures evaluated (up to 90°C). However, as noted above, some data suggest that the variations induced by the type of food being measured become less significant at higher temperatures. Therefore, these results suggest that with improvements in the type of transducers used, the physical geometry of the measured volume (e.g., smaller pans or pipes), and obtaining measurements at higher temperatures the sonic sensor system may prove feasible for the food processing industry.

Recommendations for completion of this project are summarized below:

- Better development of the relationship between temperature and the speed of sound for a number of foods that are of interest to the NFPA.
- The performance of a series of measurements using the redesigned system on specific food types and use the data to benchmark the tomography

calculations so that the uncertainties associated with measurements are adequately defined. The parameters that should be addressed include food temperature, food consistency, and measurements at canning temperatures.

- Based on the previous measurements and calculations, in collaboration with the NFPA, completion of the assembly and testing a fixed array pipe prototype with transducers in a configuration that can be used at the selected NFPA test facility.
- The performance of sonic sensor measurements at the NFPA facility to assess the effects of an actual industrial environment on the system.

Following completion of the series of measurements and calculations, it should be possible to define the uncertainties and determine the requirements for a production food temperature measurement system. Use of aseptic processing techniques with adequate temperature measurements can be expected to be valuable to many parts of the food industry with considerable cost savings and increases in food quality.

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Sonic Temperature Sensor for Food Processing (Draft)

1. INTRODUCTION

1.1 Background

The U.S. food processing industry has invested heavily in the technology for the safe processing of canned foods. The technology has a number of safeguards to ensure that food is processed properly and efficiently because food processing is energy intensive. A key problem for the food processing industry is the difficulty of accurately measuring the temperature of particulate foods during processing. Improvements in this process can result in significant improvements in both the cost and quality of processed foods. Successful development of a system that can be used to measure the temperature of particular foods would allow a major shift to the use of an aseptic processing method that does not require the use of canning and pressure cooking methods to ensure that the food is adequately cooked. Estimated reductions in national food processing energy usage are on the order of 0.01 quads/year.

The objective of the sonic temperature sensor for food processing project is to develop a prototype sensor to noninvasively measure the interior temperature of particulate foods during processing. The sensor uses the material property in which a change in the temperature of a material results in a corresponding change in the speed of sound as it passes through the material. The approach for the sonic sensor system is to determine the speed of sound using a number of sensors and then determine the temperature inside particulate foods using a tomographic reconstruction process.

The project began in 1991 as an initial assessment of the speed of sound moving through foods as a function of temperature. This initial assessment was performed primarily with potatoes and indicated that differences were discernible in the speed of sound moving through a potato as a function of temperature. Following the initial tests, a collaborative effort was begun with the National Food Processors Association (NFPA) to develop the technology. The project was divided up into two phases. The first phase was to develop a stationary prototype that could be used on canned foods, and the second phase was to develop a sensor that could be attached to piping for use as an online measurement for aseptic processing. The online system would be tested at the NFPA processing test facility.

The initial prototype was completed, and tests were performed to assess the speed of sound as it passes through some materials. However, initial tests indicated that the original prototype had a number of problems that prevented accurate acquisition of the data needed for tomographic processing. Therefore, additional modeling of the process was performed and verification measurements were taken using a state-of-the-art commercial system. Encouraging results were obtained, which suggested that though the initial schedule for the project could not be met, completing the project was possible. The objective of this report is to summarize the current state of the project, which includes both theoretical calculations and actual measurements of the speed of sound, and recommendations for completion of the project.

1.2 Technical Basis

The sonic sensor system, as visualized for an aseptic processing facility, consists of an array of transducers equally spaced around the circumference of a pipe. A schematic view of such an arrangement is presented in Figure 1. The center lines of the transducers all lie in an image plane that is perpendicular to the center axis of the pipe.

Measurements of the time of flight (TOF) of ultrasonic pulses between pairs of transducers are obtained to estimate sound speeds at points within the pipe. Because of ultrasonic-beam-width restrictions, measurements cannot be obtained between transducer pairs that are too close. In Figure 1, transducer pairs situated closer than 96 degrees cannot "see" each other. Obviously, a broad beam width is preferred over a narrow one because more measurements result in better sound-speed estimates. For the geometry depicted in Figure 1, a total of 225 TOF measurements will be taken.

Project investigations focused on the practical aspects of obtaining TOF measurements and also on computer simulations. Laboratory TOF measurements were obtained from a variety of food samples and nonfood samples using several different transducer sizes and frequencies. The measurements provided insight into the kinds of foods suitable for inspection by this method as well as an understanding of transducer limitations and requirements. Near the conclusion of the investigations, TOF measurements were obtained using a transducer geometry that mimicked a pipe array. Sound-speed maps were estimated from these measurements that validated the simulation results.

Computer simulations were conducted to gauge the performance of the inspection method and to identify implementation issues. The algorithm for the sound-speed estimation used for this work is based on a model of sound propagation that includes some known simplifications (e.g., approximations) for performance reasons. Simulations were employed to evaluate the effects of these simplifications and were used to calculate estimates of spatial resolution and sound-speed resolution.

Figure 1. The sonic sensor system consisting of an array of transducers mounted around the circumference of a pipe. (Thirty transducers are shown. Because of beam-width restrictions, the nearest receiving transducer is separated by 96° from the transmitting transducer. The sequence of drawings shows how the transmitter position shifts between sets of measurements.)

2. THEORETICAL BASIS

2.1 Estimation Process

An estimation algorithm is used to analyze TOF measurements to produce a two-dimensional map of sound speeds within the pipe. The choice of algorithms for this project was, to a significant degree, dictated by the performance requirement of generating at least one sound-speed map per second. To meet this requirement, it was necessary to adopt a simplified model of sound propagation in which sound travels only along straight lines between transmitter and receiver. That is, it was assumed that refraction (both in-plane and out-of-plane) and diffraction can be ignored.

The estimation process requires knowledge of precisely at which point each ultrasonic pulse originates and at which point it is detected. This information is not easy to determine for real transducers with finite dimensions. End-point locations vary as a function of the relative positions of the transducers as well as the physical properties of objects in the sound field. A sound-speed estimation algorithm could not include a detailed model to compute transducer origins because of the speed requirement. An approximate solution has been implemented in which the effects of finite transducer size are accounted for in a correction process that will be described later.

The estimation algorithm assumes that the two-dimensional sound-speed map can be accurately represented as a series expansion of the form

$$s(x,y) = \sum_{i=1}^N a_i b_i(x,y) \quad (1)$$

where

$s(x,y)$ = value of the sound speed at location (x,y)

b_i = two-dimensional local basis functions arranged on a square grid

a_i = coefficients of the basis functions.

The local basis functions used in this application are overlapping cubic B-splines. The linear process resulting in TOF measurements can then be represented as

$$y = Ha + v \quad (2)$$

where

y = TOF measurement vector

H = constant matrix relating TOF measurements to basis function coefficients

a = vector of basis function coefficients (to be estimated)
 v = measurement noise vector.

The matrix H depends only on the relative positions of the transducers and is computed just once for a given transducer arrangement. With prior statistical knowledge of v and a and the assumption of Gaussian statistics, the maximum a posteriori estimate of a is

$$\hat{a}_{MAP} = (V_a^{-1} + H^T V_v^{-1} H)^{-1} (H^T V_v^{-1} y + V_a^{-1} \mu_a) \quad (3)$$

where noise, v , is assumed to be zero mean with variance V_v , and the coefficients, a , are assumed to have mean μ_a and variance V_a . The error variance of the estimate can be expressed as

$$V_{\hat{a}} = V_a - V_a H^T (V_v + H V_a H^T)^{-1} H V_a \quad (4)$$

For this study, it was assumed that noise, v , is uncorrelated (V_v is diagonal) and the coefficients of variance V_a decrease linearly to zero as distance between basis functions increase. The signal-to-noise ratio (SNR) is defined as the ratio of the diagonal components of V_a to the diagonal components of V_v . The assumed SNR of an estimator (estimation matrix) is a design parameter. For this work, SNRs of 100, 1,000, and 10,000 were assumed.

The basis functions $[b_i(x,y)]$ in Equation (1)] are assumed to be arranged on a square grid. The spacing of the basis functions affects the spatial resolution of the sound-speed maps and the sensitivity of the estimation process to measurement noise and modeling noise. As the spacing between the basis functions decreases, it is possible to produce more detailed images—that is, the spatial resolution increases. On the other hand, when the number of basis functions increases, the number of coefficients to be estimated in Equation (2) also increases. Without a corresponding increase in the number of TOF measurements, the solution to Equation (2) becomes more sensitive to noise. Equation (2) will become underdetermined if the basis functions become dense enough, and a solution will not be obtainable.

A 20-by-20 basis function grid was used in this study. This basis function density was determined by experiment to represent a reasonable tradeoff between spatial resolution and noise immunity.

Ideally, it would be possible to precisely reproduce any sound-speed pattern that may occur in the image plane by using a linear combination of basis functions. In reality, this is not the case. Some patterns, especially those that contain discontinuities, cannot be matched exactly. The inaccuracies that occur in the calculated sound-speed maps are attributed to modeling noise. As an example, Figure 2 shows the locations of three circular regions within a circular pipe in which the sound speed is 5% greater than that in the surrounding medium. Figure 3 is a surface plot showing a least-mean-squared-error approximation to the sound-speed map depicted in Figure 2, assuming a 20-by-20 basis function grid. If the basis functions were capable of duplicating the sound-speed distribution exactly, three cylinders of equal height would appear in Figure 3.

Figure 2. The locations of three circular regions of varying density in which the sound speed is 5% greater than that in the surrounding fluid. (The same geometry is assumed for several of the simulation results discussed in this report.)

Minimum norm fit to three cylinders

Figure 3. The closest approximation to three cylinders using a 20-by-20 grid of cubic B-splines. (The inaccuracies are attributed to modeling noise.)

2.2 Practical Aspects of Measuring Time of Flight Through Food

Ultrasound transmission through canned corn, peas, and diced carrots was studied. The vegetables were placed in a rectangular plastic container with just enough water to fill the gaps. A few different transmitters were studied: four 0.5-in. transducers were used with center frequencies in the 1-to-15 MHz range, and a 0.054-in. pinducer also was used. Measurements were obtained using a Matec Explorer 9000 ultrasonic instrument and two different pulsers: a square wave pulser and a spike pulser. The sound attenuation in db/in. was determined by comparing the water-filled container to the vegetable-filled container. The conclusions are as follows:

- Corn and peas are very attenuative compared to the diced carrots and may be difficult to work with at frequencies greater than 5 MHz
- In all cases, transit times were less through vegetables than through water, which indicates that the speed of sound of the subject vegetables is high
- The vegetables generally act as a low-pass filter (greater than 3 MHz)
- Pinducers do not have adequate power to penetrate 2.65 in. of dense food particles, indicating that the use of point-source transmitters may be ineffective in some situations
- The square-wave pulser provides far better penetration than a spike pulser, which indicates that narrow band transducers and narrow band excitation is preferable.

While transmission of an ultrasonic pulse is detectable through canned corn and peas when the transmitting and receiving transducers share the same axis, the attenuation is probably too high for the vegetables to be inspected using a pipe array sensor. In the pipe array sensor, most TOF measurements will be made between off-axis transducer pairs. The ultrasonic signal emitted in the direction of an off-axis transducer is generally weaker than in the on-axis direction and grows weaker as the off-axis angle increases. Corn and peas are both surrounded by a semi-rigid shell, which might explain the difference in attenuation when compared with diced carrots. As discussed in Section 3.5, the spatial resolution is too poor to inspect objects the size of corn, peas, or diced carrots anyway.

In some experiments with canned corn and peas, the transmitted ultrasonic pulse appears to be delayed by the vegetables—that is, sound speed in water appears greater than that which propagates through vegetables. The difference in the sound speed suggests that the transmitted ultrasonic signal propagates around the vegetable particles by scattering or diffraction or both. The signal penetrating the vegetables apparently suffers so much attenuation that it becomes undetectable. The scattered and diffracted signals are of no use for sound-speed estimation because the interior of the food particles is not sampled.

Ultrasonic pulses propagating through corn, peas, and diced carrots appeared to undergo low-pass filtering. It is not known whether the filtering is caused by particle size or material properties. If the filtering is caused by material properties, to minimize their effects with adequate measurement accuracy. The tradeoff between penetration and measurement accuracy is a design consideration that will have to be addressed for each different geometry and food type.

Some problems are encountered when attempting to conduct controlled laboratory experiments with food samples. The sound speed of food samples varies between samples and is nonuniform within a sample. In addition, it is difficult to create a food sample with a precise cylindrical shape, and food samples deteriorate with use. Because of such problems, a search was conducted for a suitable plastic phantom to use instead of food. An ideal phantom would have a sound speed of approximately 5% greater than water (approximately 1.55 mm/ μ s), would have uniform material properties, and would be cylindrical in shape. No solid material could be identified that met these requirements. Therefore, a thin-walled plastic tube filled with castor oil (sound speed of 1.55 mm/ μ s) was tested with a through-transmission yoke. The castor oil phantom produced acceptable results. However, in the NFPA scanning system (used to mimic a pipe transducer array), the phantom produced results that were discontinuous with the water. The plastic shell apparently had a greater effect than expected at grazing angles.

2.3 Transducer Beam-Width Considerations

A physical transducer has a beam width that is something less than 180 degrees. For the sonic sensor system, transducer beam width determines the number of TOF measurements that will be available for sound-speed estimation. In general, better sound-speed estimates result from more measurements. However, estimation errors caused by a restricted beam width exhibit a spatial dependence. As the beam width decreases, sound-speed estimates near the pipe wall deteriorate much more rapidly than near the center of the pipe. Equation (4) is useful for investigating the spatial dependence of estimation error on the beam width. The error variance was calculated for the case of 45 equally spaced transducers. The calculations were done for three different beam widths and three measurement noise levels for each beam width. For the highest level of measurement noise, the standard deviation of added noise was 0.1% of the average TOF along a central chord. Noise levels of 0.03% and 0.01% also were used. The results appear in Figure 4. The standard deviation of estimation error is presented in temperature units changes in sound speed and temperature variations directly correlate. Experiments with cooked potatoes at 120°C have shown that the speed of sound decreases 0.2% for each increase in temperature of 1°C. For this application (aseptic processing), temperature changes are more meaningful than changes in the speed of sound.

In Figure 4, the standard deviation of estimation error is displayed as a function of position along a central chord of the circular pipe. Pipe radius is normalized to 0.5 units. Transducers are point sources and point detectors. Refraction is not considered. It is clear that beam width has a much larger effect on temperature estimates near the pipe wall than near the center. The estimation error is essentially unchanged in the center half of the pipe as the beam width shrinks from 172 to 92 degrees. As the beam width shrinks more to 28 degrees, estimation error is significantly larger everywhere except for a small area near the center.

The beam width of a typical unfocused transducer is a function of diameter and frequency. Beam width (or beam spread) is given by

$$\theta/2 = \sin^{-1} k\lambda/d$$

where

Figure 4. The standard deviation of temperature estimation error as a function of position along a central chord of circular pipe for 45 equally spaced transducers. (Calculations were done for three beam widths and for three levels of measurement noise for each beam width. For the highest level of measurement noise, the standard deviation of added noise is .1% of the average time of flight along a central chord. Values of .03% and .01% also are used. The beam width has a much larger effect on estimation accuracy near the pipe wall than at the center.)

$\theta/2$	=	half-angle of beam spread
k	=	constant representing drop in beam intensity
λ	=	wavelength
d	=	diameter of the active element.

Using the -6 db points, $k = 0.72$, the beam spread is calculated to be 11 degrees for a pinducer with an active element diameter of 0.054 in. (1.3 mm). The useful beam spread for the transducers empirically was determined to be approximately 14 degrees (at approximately -12 db). Referring to Figure 4, the beam spread (which is 28 degrees at full width) would result in a very small region of acceptable accuracy near the center of the pipe. A wider beam spread is required, but transducers with smaller diameters do not produce enough power to penetrate typical food densities. The pinducers used here, though adequate for one or two small cooked potato pieces, do not produce enough power for realistic food densities. An alternative solution is to use a shaped transducer (i.e., convex) to produce a higher-energy, spherical wave front. The option may provide the desired wave front, but the cost of building the customized transducers would be higher than standard transducer designs. Attenuation and field of view are both affected by transducer characteristics; therefore, the transducer design is an important issue that must be addressed during future work.

3. MEASUREMENT RESULTS

3.1 Effects of Refraction

Refraction affects the trajectory of an ultrasonic pulse as it travels between a pair of transducers. In general, the pulse does not travel along a straight line. However, the straight line approximation is valid when variations in sound speed are small. Investigations were conducted to determine whether the straight-line approximation is valid for sound-speed variations typical of aseptically processed foods. The investigations consisted of laboratory measurements and computer simulations.

A pair of transducers was mounted in a yoke, as depicted in Figure 5, so that the transducers faced each other and shared the same center axis. The yoke was translated so that cylindrical samples of potato and polyvinyl chloride (PVC) plastic passed between the transducers. The axis of each cylindrical sample was perpendicular to both the transducer axis and the direction of motion of the yoke-mounted transducers. The sound speed in the samples was greater than the sound speed in water. The general shape to be expected from a plot of TOF versus transducer position (the yoke position) is shown in Figure 6. The receiving transducer was a pinducer in all tests. The transmitting transducer was a pinducer in the refraction experiments described here.

The food samples used in the experiments were cooked potatoes. The samples were cut, using a coring tool, into cylindrical pieces about 2 in. long with a diameter of 0.75 in. Samples cut from PVC plastic rods also were used. The PVC rods also had a diameter of 0.75 in.

By knowing the size of the sample, the distance between the transducers, and the sound speed in water, it was possible to determine the average sound speed in the samples from TOF measurements. The sound speed in the cooked potato samples was found to be $1.54 \text{ mm}/\mu$, about 5% greater than the sound speed in water. The sound speed in the PVC samples was $2.31 \text{ mm}/\mu\text{s}$.

From the sample size and sound speed, theoretical TOF values were calculated for two different models of sound propagation. The simplest model assumed no refraction or diffraction. A more complicated model assumed refraction but no diffraction. Measured TOF values were compared with TOF values calculated from the models.

The results of measurements from a potato sample and a PVC sample are shown in Figure 7. A pinducer transmitter was used for the measurements. The TOF values calculated using the two models described above also are shown. The refraction effects are clearly evident. It also is apparent that the simple refraction model does a fairly good job of predicting TOF values. However, the critical issue is determining the effects of refraction on the estimation of sound speed using the simplified linear estimation scheme described above. Computer simulations were conducted to resolve the issue. TOF values were computed using a realistic model of sound propagation that incorporated the effects caused by refraction and transducer size. The TOF values were then processed by the estimation algorithm to yield sound-speed maps. The results of these simulations are presented in Section 3.4.

Figure 5. A pair of transducers mounted in a yoke for laboratory time-of-flight measurements. (The transducers face each other and share the same center axis. The yoke was translated so that cylindrical samples of potato and polyvinyl chloride plastic passed between the transducers. The axis of each cylindrical sample was perpendicular to both the transducer axis and the direction of motion of the yoke-mounted transducers.)

Figure 6. The general shape of a plot of time-of-flight versus transducer position. (The shape was obtained using the arrangement depicted in Figure 5.)

Figure 7. Time-of-flight measurements from a potato sample (top) and a polyvinyl chloride plastic sample (bottom). (Simulated results also appear. Simulations including the effects of refraction clearly are more accurate. Refraction effects cause the cylinder samples to appear noticeably wider.)

3.2 Transducer Size Effects

Transducer size effects are illustrated in Figure 8. The top graph shows TOF measurements obtained from a potato sample using two different transmitter sizes: a pinducer and a 0.5-in. transducer. The bottom graph shows TOF measurements that were obtained using four different transmitter sizes. The apparent width of the sample increases as the transmitter diameter increases for both potato and PVC samples.

A model was developed to account for transducer size effects. It assumes that a finite-size transducer can be modeled as a dense linear array of point transducers. To calculate the TOF between a pair of transducers, the TOF is first calculated for all combinations of point-transmitter point-receiver pairs from the linear arrays constituting the two transducers. The smallest calculated value is accepted as the TOF between the finite-size transducer pair. The TOF values computed using this model are provided in Figure 9. Two simulated TOF curves are shown: one that includes the refraction effects alone and one that includes both refraction and transducer size effects. The sample is assumed to be a cylinder with a diameter of 0.75 in. and a sound speed of $1.54 \text{ mm}/\mu\text{s}$, which is the same as the potato samples. Computed transducer size effects are similar in magnitude to the measured effects evident in the top graph in Figure 8.

Transducer size greatly affects the sound-speed maps estimated from TOF measurements, but the effect can be reduced significantly through the use of a simple correction scheme. The sound-speed map appearing at the top of Figure 10 was computed from simulated TOF values that include both refraction and transducer-size effects. These TOF values were calculated for 45 evenly spaced transducers. The pipe diameter was assumed to be 6 in. and the transducer diameter was assumed to be 0.25 in. Transducers closer than 96 degrees were assumed to be unable to detect each other. A single cylinder, which had a diameter of 1.2 in. and a sound speed of 5% greater than that in the surrounding fluid, was placed at the center of the pipe. It is apparent from the figure that transducer-size effects are overwhelming. However, the bottom graph in Figure 10 shows that the correction scheme is capable of removing most of the effects caused by transducer size. The TOF values used to generate the bottom graph were corrected by subtracting from them the TOF values for an empty field—that is, the TOF values for a constant-valued temperature field with a sound speed equal to that in the surrounding fluid.

3.3 Monte Carlo Experiments to Evaluate the Effects of Refraction and Transducer Size

Computer simulations were conducted to evaluate the effects of refraction and transducer size on sound-speed maps. TOF measurements were calculated for numerous cases in which cylinders were randomly positioned within the center region of a 6-in. pipe. The diameter of the center region was 3 in. A cylinder was considered to be within the center region if its center lay within 1.5 in. of the pipe center. Forty-five 0.25-in. transducers were assumed to be evenly spaced around the circumference of the pipe. The diameters of the cylinders were 1.2 in. The sound speed of the cylinders was 5% greater than that in the surrounding fluid.

Noise was added to the simulated TOF measurements. Sound-speed maps were estimated for three different SNR of 100, 1,000, and 10,000. For the SNR of 100, the standard deviation of additive measurement noise was 0.1% of the mean TOF along a central chord. For the SNR of 1,000, the value was 0.0316%, and for the SNR of 10,000, the value was 0.01%. For a 60-in. pipe, the values correspond to measurement error standard deviations of approximately 103, 33, and 10 nanoseconds, respectively.

Figure 8. The effects of transducer size. (The top graph shows time-of-flight measurements obtained from a cylindrical potato sample using a pinducer and a half in. transducer. The bottom graph shows measurements obtained from a PVC plastic cylinder sample using four different transducer sizes. The wider transducers cause the cylinder samples to appear to be noticeably wider.

Figure 9. Time-of-flight measurements for two different transducer diameters computed using a model developed to simulate the effects of finite transducer size.

45 transducers, nearest transducer=96°
SNR=1 000, 20x20 basis fn. grid
.25" transducer, 6" pipe, includes refraction

45 transducers, nearest transducer=96°
SNR=1 000, 20x20 basis fn. grid
.25" transducer, 6" pipe, includes refraction

Figure 10. The effects of transducer size on sound-speed map estimation (top graph) and the improvement achieved through the use of a sample correction scheme (bottom graph).

Sound-speed maps were analyzed by computing the statistics of pixels inside and outside the randomly positioned cylinders. A pixel was considered inside a cylinder if its center lay within 0.3 in. of the actual center of the cylinder. A pixel was outside if its center lay more than 0.9 in. from the center of all cylinders. Pixels were square with a side dimension of 0.12 in. The following statistics are reported: the mean value within all cylinders, the standard deviation of that mean, the mean of the peak (maximum) values within all cylinders, and the standard deviation of that mean.

Experiments were first conducted with ideal TOF values—that is, TOF values computed with no refraction or transducer-size effects. The results of these experiments is summarized in Table 1. The estimation error is presented in temperature units as described above. A 0.2% change in sound speed translates to a temperature decrease of 1°C.

Experiments were next conducted with the refraction and transducer size effects included. TOF values were used that were calculated with these effects. The correction for the transducer-size effects described earlier was then applied to the TOF values. Table 2 summarizes the results of these experiments.

The mean error and the mean peak error represent estimator biases for which corrections can be made. The important quantities are the standard deviations of those means. When the data from all the simulated cases are combined, the refraction and transducer size effects cause the standard deviation of the inside mean to increase from 0.84 to 1.49. The standard deviation of the mean peak value increases from 0.5 to 1.5. The number of cylinders positioned in the image plane of the pipe does not have a significant effect on the accuracy of the calculated sound-speed maps.

Figures 11 through 15 show sound maps computed for a variety of SNR levels and containing from one to three cylinders. The maps on the left in each figure are generated from simulated TOF measurements that do not include the effects of refraction or transducer size and do not include measurement noise. The center maps are generated from simulated TOF measurements that include the effects of refraction and transducer size, but contain no measurement noise. The maps on the right were generated from simulated TOF measurements that include the effects of refraction and transducer size as well as measurement noise.

The parameters (the number of transducers, transducer diameters, sound speeds, etc.) used to simulate TOF measurements and compute the sound-speed maps are the same as those used for the Monte Carlo experiments discussed above. In the figures, the sound-speed maps are normalized so that the pipe diameter is 1 in., the cylinder diameter is 0.2 in., and the transducer diameter is 1/24th of the diameter of the pipe. The normalized dimensions are equivalent to a pipe diameter of 6 in., a cylinder diameter of 0.12 in., and a transducer diameter of 0.25 in.

Table 1. A statistical summary of the results of computer simulations in which the effects of refraction and transducer size were ignored.

Number of Cylinders Simulated	Signal-to-Noise Ratio (SNR)	Mean Error Inside	Standard Deviation of Mean Error	Mean Peak Error Inside	Standard Deviation of Peak Error	Number of Experiments
1	100	-1.1°	1.1°	-2.5°	.7°	1,000
2	1,000	-1.1°	.7°	-2.1°	.3°	1,000
3	10,000	-1.1°	.6°	-2.0°	.3°	1,000
1	100	-1.0°	1.1°	-2.5°	.8°	1,000
2	1,000	-1.1°	.7°	-2.1°	.4°	1,000
3	10,000	-1.1°	.7°	-2.5°	.3°	1,000
1	100	-1.0°	1.2°	-2.1°	.9°	1,000
2	1,000	-1.0°	.8°	-2.1°	.4°	1,000
3	10,000	-1.0°	.7°	-1.1°	.4°	1,000

Table 2. A statistical summary of the results of computer simulations in which the effects of refraction and transducer size were included.

Number of Cylinders Simulated	Signal-to-Noise Ratio (SNR)	Mean Error Inside	Standard Deviation of Mean Error	Mean Peak Error Inside	Standard Deviation of Peak Error	Number of Experiments
1	100	1.9°	1.6°	.1°	1.6°	100
2	1,000	1.8°	1.4°	.4°	1.6°	100
3	10,000	1.7°	1.4°	.2°	1.8°	100
1	100	1.9°	1.6°	.1°	1.6°	100
2	1,000	1.9°	1.3°	.5°	1.4°	100
3	10,000	1.9°	1.3°	.6°	1.4°	100
1	100	1.8°	1.6°	.1°	1.5°	100
2	1,000	1.8°	1.6°	.5°	1.3°	100
3	10,000	1.8°	1.6°	.5°	1.3°	100

Figure 11. Sound-speed maps computed from simulated time-of-flight data with assumed signal-to-noise ratios of 100 and 1,000. [The diameter of the pipe is assumed to be 1 in. A single cylinder, with a diameter of 0.2 in., is positioned at the center of the pipe. The sound speed within the cylinder is 1.05, 5% greater than that in the surrounding fluid. Forty-five equally spaced transducers are assumed to be equally spaced around the circumference. The diameter of each transducer is assumed to be 1/24th of the diameter of the pipe. Transducers nearer than 96 degrees cannot detect each other. The sound-speed maps in the top row are generated with an estimator that assumes a signal-to-noise ratio (SNR) of 100. An SNR of 1,000 is assumed for the maps in the bottom row. Simulated TOF measurements used to generate the maps in the left column do not include the effects of refraction or transducer size, or measurement noise. Simulated TOF measurements used to generate the maps in the center column include the effects of refraction and transducer size, but contain no measurement noise. Simulated TOF measurements used to generate the maps in the right column include the effects of refraction and transducer size as well as measurement noise. For the normalized system, with a pipe diameter of 1 in. and a sound speed of 1.0 in the surrounding fluid, an SNR of 100 corresponds to measurement noise with a standard deviation of .001. An SNR of 1,000 corresponds to measurement noise with a standard deviation of .00316.]

Figure 12. Sound-speed maps computed from simulated time-of-flight data with assumed signal-to-noise ratios of 10,000 and 100. [The diameter of the pipe is assumed to be 1 in. A cylinder with a diameter of 0.2 in. is positioned at the center of the pipe. The sound speed within the cylinder is 1.05, 5% greater than that in the surrounding fluid. Forty-five equally spaced transducers are assumed to be equally spaced around the circumference. The diameter of each transducer is assumed to be 1/24th of the diameter of the pipe. Transducers nearer than 96 degrees cannot detect each other. The sound-speed maps in the top row are generated with an estimator that assumes a signal-to-noise ratio (SNR) of 10,000. A SNR of 100 is assumed for the maps in the bottom row. Simulated TOF measurements used to generate the maps in the left column do not include the effects of refraction or transducer size, or measurement noise. Simulated TOF measurements used to generate the maps in the center column include the effects of refraction and transducer size, but contain no measurement noise. Simulated TOF measurements used to generate the maps in the right column include the effects of refraction and transducer size as well as measurement noise. For the normalized system, with a pipe diameter of 1 in. and a sound speed of 1.0 in the surrounding fluid, an SNR of 10,000 corresponds to measurement noise with a standard deviation of .0001. An SNR of 100 corresponds to measurement noise with a standard deviation of .001.]

Figure 13. Sound-speed maps computed from simulated time-of-flight data with assumed signal-to-noise ratios of 1,000 and 10,000. [The diameter of the pipe is assumed to be 1 in. A cylinder with a diameter of 0.2 in. is positioned at the center of the pipe. A second cylinder, identical to the first, is positioned at $x = -.3$, $y = 0$. The sound speed within the cylinders is 1.05, 5% greater than that in the surrounding fluid. Forty-five equally spaced transducers are assumed to be equally spaced around the circumference. The diameter of each transducer is assumed to be $1/24$ th of the diameter of the pipe. Transducers nearer than 96 degrees cannot detect each other. The sound-speed maps in the top row are generated with an estimator that assumes a signal-to-noise ratio (SNR) of 1,000. An SNR of 10,000 is assumed for the maps in the bottom row. Simulated TOF measurements used to generate the maps in the left column do not include the effects of refraction or transducer size, or measurement noise. Simulated TOF measurements used to generate the maps in the center column include the effects of refraction and transducer size, but contain no measurement noise. Simulated TOF measurements used to generate the maps in the right column include the effects of refraction and transducer size as well as measurement noise. For the normalized system, with a pipe diameter of 1 in. and a sound speed of 1.0 in the surrounding fluid, an SNR of 1,000 corresponds to measurement noise with a standard deviation of .00316. An SNR of 10,000 corresponds to measurement noise with a standard deviation of .0001.]

Figure 14. Sound-speed maps computed from simulated time-of-flight data with assumed signal-to-noise ratios of 100 and 1,000. [The diameter of the pipe is assumed to be 1 in. Three cylinders, each with a diameter of 0.2 in., are positioned in the image plane of the pipe. One cylinder is located at the center of the pipe. A second cylinder is positioned at $x = -.3, y = 0$. A third cylinder is positioned at $x = .25, y = -.25$. The sound speed within the cylinders is 1.05, 5% greater than that in the surrounding fluid. Forty-five equally spaced transducers are assumed to be equally spaced around the circumference. The diameter of each transducer is assumed to be 1/24th of the diameter of the pipe. Transducers nearer than 96 degrees cannot detect each other. The sound-speed maps in the top row are generated with an estimator that assumes a signal-to-noise ratio (SNR) of 100. An SNR of 1,000 is assumed for the maps in the bottom row. Simulated TOF measurements used to generate the maps in the left column do not include the effects of refraction or transducer size, or measurement noise. Simulated TOF measurements used to generate the maps in the center column include the effects of refraction and transducer size, but contain no measurement noise. Simulated TOF measurements used to generate the maps in the right column include the effects of refraction and transducer size as well as measurement noise. For the normalized system, with a pipe diameter of 1 in. and a sound speed of 1.0 in the surrounding fluid, an SNR of 100 corresponds to measurement noise with standard deviation of .001. An SNR of 1,000 corresponds to measurement noise with a standard deviation of .00316.]

Figure 15. Sound-speed maps computed from simulated time-of-flight data shown with an assumed signal-to-noise ratio of 10,000. [The diameter of the pipe is assumed to be 1 in. Three cylinders, each with a diameter 0.2 in., are positioned in the image plane of the pipe. One cylinder is located at the center of the pipe. A second cylinder is positioned at $x = -0.3$, $y = 0$. A third cylinder is positioned at $x = -0.25$. The sound speed within the cylinders is 1.05, 5% greater than that in the surrounding fluid. Forty-five equally spaced transducers are assumed to be equally spaced around the circumference. The diameter of each transducer is assumed to be 1/24th of the diameter of the pipe. Transducers nearer than 96 degrees cannot detect each other. The sound-speed maps are generated with an estimator that assumes a signal-to-noise ratio (SNR) of 10,000. Simulated TOF measurements used to generate the maps in the left column do not include the effects of refraction or transducer size, or measurement noise. Simulated TOF measurements used to generate the maps in the center column include the effects of refraction and transducer size, but contain no measurement noise. Simulated TOF measurements used to generate the maps in the right column include the effects of refraction and transducer size as well as measurement noise. For the normalized system, with a pipe diameter of 1 in. and a sound speed of 1.0 in the surrounding fluid, an SNR of 10,000 corresponds to measurement noise with standard deviation of .0001.]

3.4 Spatial Resolution for the Sound-Speed Map Estimation Process

A series of experiments were conducted to determine the spatial resolution of sound-speed maps estimated from TOF measurements. The TOF measurements were simulated for several different cylinder diameters. Refraction effects, transducer-size effects, and measurement noise were included in the TOF calculations. In all cases, the sound speed in the cylinders was 5% greater than that in the surrounding fluid. The TOF measurements were simulated for 45 and 30 transducers. Beam-width restrictions were similar for both transducer arrangements. Other parameters used to simulate the TOF measurements and to compute the sound-speed maps were the same as that described in Section 2.

Figure 16 summarizes the results of the experiments for an SNR level of 1,000. The peak (maximum) sound-speed value of a cylinder is plotted as a function of the cylinder diameter. It is evident that the peak value is an accurate estimation of the actual cylinder sound speed as long as the cylinder diameter is larger than some threshold value. For a 6-in. pipe with 45 transducers, the threshold value is approximately 0.9 in. For a 6-in. pipe with 30 transducers, the threshold value is approximately 1.2 in. For a 3-in. pipe, the threshold values are 0.45 in. and 0.6 in. for 45 and 30 transducers, respectively. These values imply that (1) for a 6-in. pipe, the spatial resolutions of the sound-speed map estimation process are around 0.9 and 1.2 in. for 45 and 30 transducers, respectively, and (2) for a 3-in. pipe, the spatial resolutions are around 0.45 and 0.6 in. for 45 and 30 transducers, respectively.

3.5 Results from Actual Ultrasonic Time of Flight Measurements

Actual TOF measurements were obtained using a circular scanning system, and the measurements were used to estimate sound-speed maps. The scanning system was configured to simulate a 45-transducer pipe array. Pinducers were used for both transmission and reception. The effective beam width of the pinducers was 28 degrees (56 degrees of arc). With the narrow field of view, only points near the center of the pipe were sampled by all of the 45 transducers.

The experimental setup is depicted in Figure 17. The dimensions in Figure 17 are normalized to a pipe diameter of 1 in. The actual diameter of the "pipe" was 3.67 in. The diameter of the potato cylinders was 0.55 in. The TOF measurements were collected with a single potato sample at the center and again with the sample offset. Measurements were then obtained with potatoes occupying both center and offset positions. As is evident in Figure 17, only the center potato sample is in the field of view of all transducers. The temperature of the water bath also was varied during the experiments. Equilibrium between the potato samples and the water bath was apparently achieved at all temperature levels before TOF measurements were made.

The TOF measurements were made using the Sonix ultrasonic inspection system. The data collected were TOF measurements to the first zero crossing of the first arrival signal. Measurement resolution was 16 nanoseconds. Wave forms were averaged 16 times before zero crossings were determined to minimize the error caused by baseline noise. With the level of averaging, the standard deviation of measurement noise was less than 8 nanoseconds for on-axis transducer pairs, and less than 15 nanoseconds for transducer pairs oriented 36 degrees off-axis. The level of measurement noise is insignificant compared to other noise sources.

Figure 16. The peak sound-speed values estimated for several cylindrical samples as a function of the sample diameter. (Simulated time-of-flight measurements were used to obtain the results. In all cases, the sound speed in the sample was 5% greater than that in the surrounding fluid.)

Figure 17. The experimental setup used to obtain time-of-flight measurements for sound-speed map estimation. (One or two cylindrical potato samples were placed inside the "pipe." The 45-transducer pipe array geometry was actually achieved using a two-transducer circular scanning system.)

Figure 18 shows sound-speed maps generated from TOF measurements. An SNR level of 1,000 was assumed. Figure 19 shows a sound-speed map generated from simulated TOF measurements calculated to approximate the two-potato geometry displayed in Figure 17. The appearance of the offset potato varies somewhat between maps generated with real data and maps generated with simulated data. The difference in appearance could be caused by an inaccurate value for the sound speed for the offset potato and density variations within the potato sample.

Figure 20 shows a sound-speed map generated from actual measurements with the water-bath temperature raised to 40°C. The surface plot appears essentially the same as that obtained at room temperature, but the whole plot is elevated because the average sound speed is increased. In all, TOF measurements were obtained with the water bath at 20, 40, 50, 60, 70, 80, and 90°C. At all elevated temperature levels, the sound-speed maps appeared to be elevated versions of the maps obtained at 20°C.

Figure 21 illustrates how sound speed varies with the water-bath temperature. One curve shows the sound speed within the potato, as determined from the sound-speed maps. Another curve shows measurements obtained in pressure cooker experiments conducted previously by the Idaho National Engineering and Environmental Laboratory (INEEL). A third curve shows the sound speed in the water bath. Obviously, the pressure cooker sound speeds are significantly different from those obtained in the latest set of experiments. The reasons are unknown. The potato sound speeds obtained in the recent experiments increase at a rate slower than the sound speed in the water bath. This is in part from deterioration of the potato samples at higher temperatures. It was necessary to replace the potato samples at 90°C.

Figure 22 shows that the sound speeds estimated from TOF measurements for the water-bath region match closely with the values obtained from simple pitch-catch measurements. This information provides some validation of the estimation process. Figure 23 compares the measured water-bath sound speeds with published values for water.

45 transducers, 20x20 grid, transducer view=28 degrees, filter SNR=1000
Room temp., potato at center with normalized diameter .17, peak=1.0319

1

45 transducers, 20x20 grid, transducer view=28 degrees, filter SNR=1000
Room temp., potato off-centered with normalized diameter .17, peak=1.0204

2

45 transducers, 20x20 grid, transducer view=28 degrees, filter SNR=1000
Room temp., two potatoes with normalized diameter .17, peak=1.0292

3

Figure 18. Sound-speed maps generated from actual time-of-flight measurements. (The geometry shown in Figure 17 is used. For the first surface plot, the potato was located at the center. For the second plot, the potato was offset. In the third plot, potato samples occupied both positions.)

Simulated data, includes refraction and transducer size effects
 Cylinders at (0,0) and (.27,0), cylinder diameters=.15, sound speed=1.028
 45 transducers, 28° beam width, 20x20 basis fn. grid, SNR=1000
 Measurement noise added ($\sigma=20$ ns)

Figure 19. A sound-speed map generated from simulated time-of-flight measurements. (The simulated measurements were calculated to approximate the two-potato geometry displayed in Figure 17).

40° C, two potatoes, normalized diameter=.15, peak=1.0592
45 transducers, 28° beam width, 20x20 basis fn. grid, SNR=1000

Figure 20. A sound-speed map generated from actual time-of-flight measurements in which the water-bath temperature has been raised to 40°C.

Figure 21. The variation of sound speed with temperature. (One curve shows the sound speed within the potato sample, as determined from simulated sound-speed maps. Another curve shows the sound-speed variation within the surrounding water. A third curve shows measurements obtained in pressure cooker experiments.)

Figure 22. Water-bath sound speeds, determined from estimated sound-speed maps, compared with direct pitch-catch measurements of the water-bath sound speed. (The close correlation provides some validation of the estimation process.)

Sound Speed of Water vs Temp.

Figure 23. Measured water-bath sound speeds compared with published values.

4. CONCLUSIONS AND RECOMMENDATIONS

The sonic temperature sensor project has shown that sound speed can be determined, using a 45-transducer pipe array, to an accuracy of approximately $\pm 0.4\%$, corresponding to a temperature uncertainty of approximately $\pm 2^\circ\text{C}$. This accuracy is achieved in the central region of the pipe. The size of the central region is determined by the transducer beam width. Analysis of the estimation process indicates that TOF measurement noise will not be a limiting factor.

Laboratory measurements using food samples indicate that penetration is an important issue. Narrow-band excitation works better than broad-band excitation. Pinducers probably do not produce enough power for use in a general purpose pipe array system.

A simplified linear estimator has been used to compute cross-sectional sound-speed maps from TOF measurements. This study has shown that the simplifications, made for performance reasons, are justified; refraction effects are small, and a simple correction is capable of nearly nullifying the effects of transducer size. These conclusions are valid for sound-speed variations in the 5% range. For larger variations, the conclusions may not stand.

Simulations have shown that, for a 6-in. pipe, spatial resolution of approximately 1 in. is achievable using a transducer pipe array. For a 3-in. pipe, the resolution will be approximately 0.5 in.

Sound-speed maps obtained from actual TOF measurements compare favorably with maps obtained from simulated TOF values. The results provide validation of the estimation algorithm.

Variations in the material properties of processed foods may present problems for the implementation of the temperature measurement technique. If the sound speed in a certain type of food varies significantly between samples at canning temperatures (greater than 120°C), then it may be difficult to inspect that food type using temperature measurement technology. It has been noticed during this study that the sound speed in potato samples varies by $\pm 1.2\%$ at room temperature. The error is three times larger than the estimation error reported above. Previous INEEL research suggests that at canning temperatures, variations between same-type food samples become negligible.

Sound-speed maps ultimately must be converted to temperature maps. The conversion may not be a trivial step, especially when more than one food type is present.

Recommendations for completion of the project are summarized below:

- Better development of the relationship between temperature and the speed of sound for a number of foods that are of interest to the NFPA.
- The performance of a series of measurements using the redesigned system on specific food types and using the data to benchmark the tomography calculations so that the uncertainties associated with measurements are adequately defined. Parameters to be addressed include food temperature, food consistency, and measurements at canning temperatures.
- Based on the previous measurements and calculations, in conjunction with the NFPA, assembly of a fixed array pipe prototype using transducers in a configuration that can be used at the NFPA test facility.

- Sonic sensor measurements would be performed at the NFPA facility to assess the effects of an actual industrial environment on the system.

Following completion of the series of measurements and calculations, it should be possible to define the uncertainties and determine whether a production system is possible. Use of aseptic processing techniques with adequate temperature measurement can be expected to be valuable to many parts of the food industry because of the potential for considerable cost savings and increases in food quality.