ADVANCED INTERNAL IMAGING TECHNOLOGIES FOR VERIFICATION

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ABSTRACT
The United States Defense Threat Reduction Agency (DTRA) sponsored research at the Oak Ridge National Laboratory (ORNL) into the efficacy of infrared (IR) classification as an alternative technology verification of internal components of a canister. In our effort, dynamic IR measurements were made on a metal container. These measurements differ from normal (static) IR measurements in that changes in surface temperature profiles are monitored as an object is actively heated or cooled. We demonstrated the capability of performing these types of measurements using limited cooling in the form of vortex coolers. These coolers have no electrical requirements and use only instrument air to provide -20°C air at their exhaust port. The tests showed the ability of dynamic IR imaging to reveal information about structures inside the container not accessible with more conventional techniques like X-rays or static IR imaging. This information includes the general structure of underlying components in thermal contact with the shell of the casing as well as the radiative power of embedded thermal sources. The technique thus has the potential for providing two independent parameters, internal structure and source power, that could compliment information from other existing technologies for internal structure categorization.

Another technology that has significant implications for internal verification of containers is acoustic tomography. Acoustic tomography has been used extensively at ORNL to provide information about underground structures and in imaging studies for small animal research. Given efficient internal acoustic coupling in containers, this technique provides high spatial resolution information about contents that could form the basis of a unique signature per item for verification.

I. Dynamic IR Technologies

Normal infrared (IR) imaging uses the blackbody thermal emission from an object to remotely characterize its surface temperature distribution. Little, if any information is available with normal IR imaging about defects, structures, or material property variations lying beneath the surface. Dynamic IR imaging, on the other hand, measures the change in surface temperature distribution over time as the object is heated or cooled and is sensitive to subsurface structures or material properties. The heating and cooling can take several forms from variations in ambient temperature due to the solar diurnal cycle to active step or cyclical heating or cooling using refrigerants or resistive heating elements. In our tests, we experimented with various cooling methods, beginning with applying liquid nitrogen to the surface of container and later using commercially available vortex coolers. Even with liquid nitrogen cooling, the maximum temperature change inside the container (as recorded with thermocouples) is only 6 to 7°C (see the cooling curves in Figure 1).

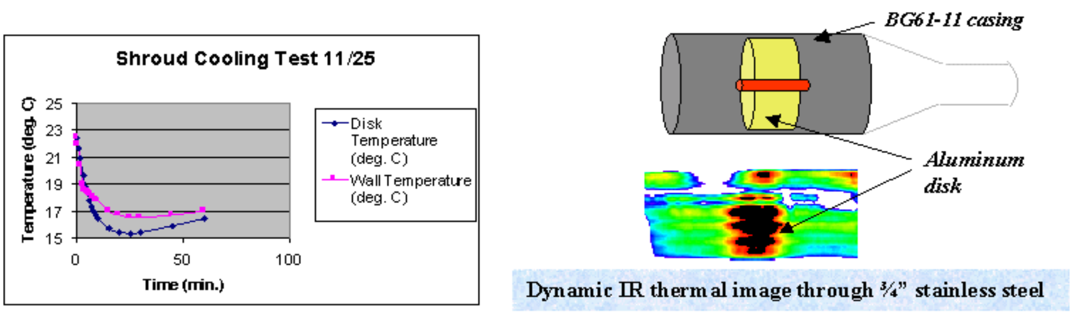

Figure 1. Initial Dynamic IR Experiments

Figure 1 also shows our experiment configuration for this project. An aluminum disk was inserted in a 2-cm. thick stainless steel container as shown. Embedded in the aluminum disk is a small cylindrical resistive heating element, simulating a thermal source inside the container. The dynamic IR image in Figure 1, below the cartoon of the container, clearly reveals the presence of the aluminum disk. Imaging the inserted disk is an extremely difficult task. Even with X-rays the energy required to penetrate the stainless steel casing is too high to "see" the aluminum material. With this experimental configuration we were successfully able to see the internal aluminum disk and test a variety of parameters including the sensitivity of dynamic IR imaging to cooling rates and amplitudes as well as to the power applied to the heating element.

To facilitate cooling we designed and fabricated a removable shroud that fit over the container and provided a confined space for applying the liquid nitrogen. The shroud (see Figure 2) was developed to better control the cooling process by providing uniform cooling over a fixed time interval. During the tests, four liters of liquid nitrogen were poured into the shroud and the shroud was then removed after one minute. Quantifiable results could then be obtained as the power to the heating cartridge inside the casing was varied.

Initially in our tests, liquid nitrogen was used to cool the surface since it provides a dramatic step change in temperature and large thermal gradients. Realistically though, a less severe means of cooling is preferred. In a second set of tests, limited cooling was used on the container via vortex coolers. These coolers run on standard instrument air (no electrical requirements) and provide -20°C air at the exit nozzle. The principle of the coolers was discovered in 1930 by French Physicist George Ranque. Room temperature air is forced into a column that is designed to produce a vortex (like a tornado) as shown in Figure 3. The vortex travels down the column and a portion of the circulating air exits the end of the column. The remaining air returns down the center of the column (traveling the opposite direction as the incoming air), transfers heat to the entering vortex, and is super-cooled. Therefore, one exhaust port of the vortex cooler emits hot air and the other, the super-cooled air.

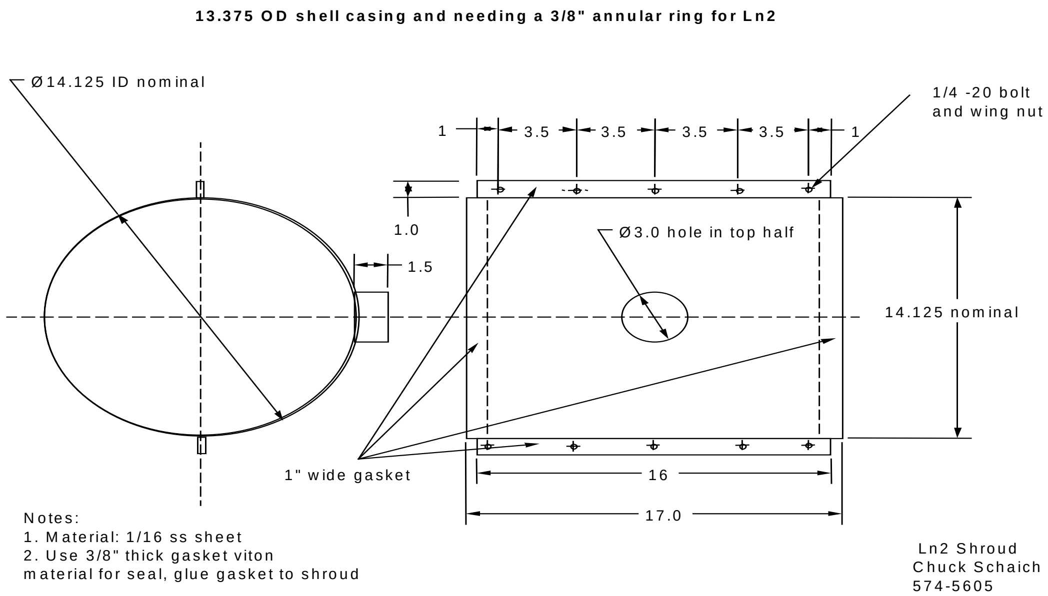

Figure 2. Liquid Nitrogen Cooling Test Ring

II. Dynamic IR Experimental Results

A. Sensitivity to internal structure

One application of dynamic IR imaging involves the use of the technique to categorize the internal structure of a container. Our initial tests were directed toward optimizing the imaging of the inserted aluminum disk through the 2-cm. stainless steel container. In these tests, the container was cooled using liquid nitrogen for a time interval of one minute. The external surface of the container directly over the disk was then imaged using an InSb, 256x256 infrared camera (manufactured by Amber) as the casing returned to room temperature. Figure 4 shows typical IR images of the container at seven and nine minutes after the application of liquid nitrogen. The images were obtained by subtracting the frame taken at, for instance, nine minutes from a reference frame taken several minutes after the cooling with liquid nitrogen. Some contrast enhancement was performed to compensate for thermal noise sources and for the large dynamic range encountered in the measurements. With these simple image-processing techniques (i.e., image subtraction and contrast enhancement) the disk is easily imaged.

B. Sensitivity to embedded heat source

A second piece of information needed for categorizing the container is the presence of nuclear sources. We performed a series of tests with the container casing to determine the sensitivity of the dynamic IR surface characterization method to embedded heat sources. The test platform again consisted of the 2-cm. thick stainless steel container with a 7.6-cm thick aluminum disk inserted with a slip fit and a variable heating cartridge (0 to 12 watts) embedded in the disk. In the test, we used the cooling shroud to reproducibly cool the section of the container containing the disk and cartridge with liquid nitrogen. We performed four separate tests where we fixed the power on the embedded heating cartridge (0, 4, 8, and 12 watts) and let the

Vortex coolers

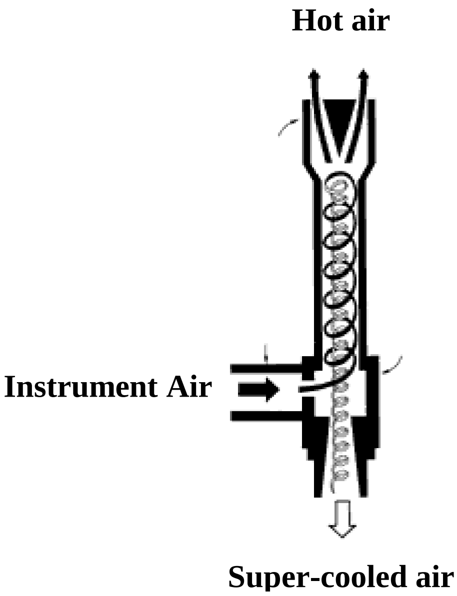

Figure 3. Vortex Coolers: Picture and Principle (reproduced with permission from ITW Vortec)

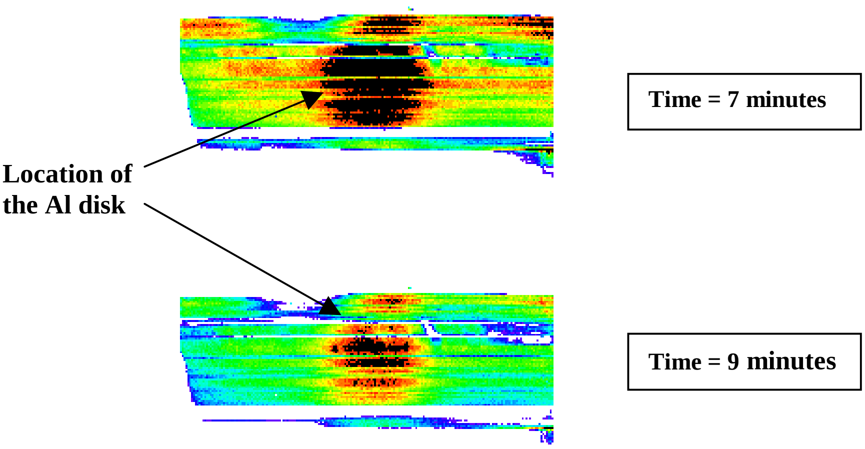

Figure 4. Imaging Internal Structure with Dynamic IR Techniques

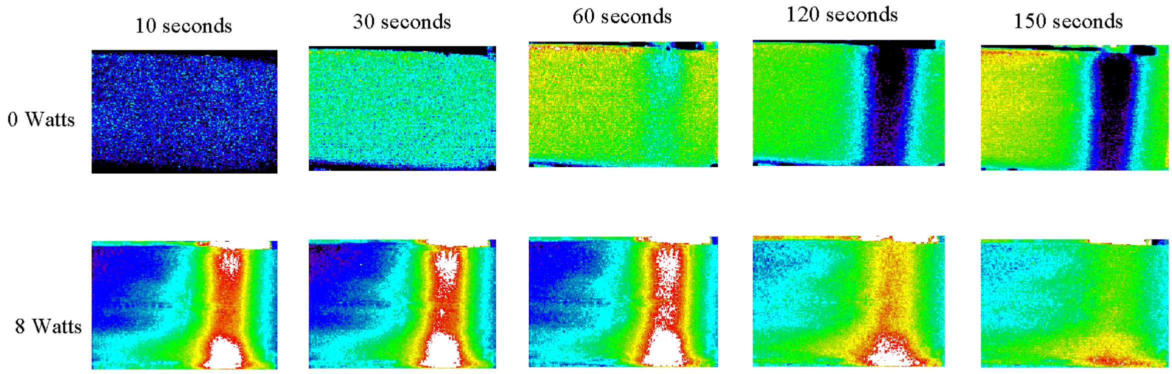

Figure 5. Sensitivity of Dynamic IR Imaging to Internal Heating Sources

container with disk reach equilibrium over a 24-hour period. We cooled the shell for one minute with liquid nitrogen and recorded a series of IR images of the surface of the container after the shroud was removed. Figure 5 shows typical images from the tests. The images show qualitatively the dependence between applied power and the extent of the thermal boundaries of the internal aluminum disk at prescribed times after the application of liquid nitrogen. We performed additional analysis of these images using wavelets and showed a quantitative relationship between applied power and image energy. These results are presented in the Wavelet Analysis Section below.

C. Sensitivity using limited cooling

To be useful, an alternate cooling method to the liquid nitrogen is preferred and was investigated. We explored limited cooling of the container and inserted aluminum disk using vortex coolers (described above) that operate using room temperature instrument air and produce -20°C air at the exit nozzle without any electrical requirements. These vortex coolers provide substantially less energy to cool the casing than the liquid nitrogen and therefore make the measurement very challenging. In a series of tests, we tried various configurations using two 35-cfm vortex coolers to extract the dynamic IR image of the inserted disk. We discovered that the keys to making dynamic IR measurements with limited cooling are 1) controlling the surface emissivity and 2) thermally exciting the surface such that a thermal wave propagates completely through the wall. The resulting images are shown in Figure 6. The first row shows the test with no power applied to the aluminum disk and the second with 8 watts applied as a function of time after the vortex coolers were turned on. With this new configuration we were able to see the disk with embedded heat source without having to difference images and also before the thermal wave completely propagates through the wall (i.e., 10 seconds, 2nd row image). The differential measurements are then important to determine the power present in the heat source and to see internal structure when no heat source is present (i.e., 120 and 150 seconds, 1st row images). Also, by making these changes to our measurement configuration we were able to achieve better spatial resolution than previous tests with liquid nitrogen.

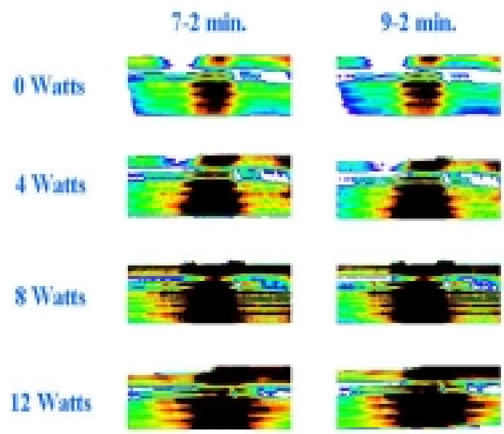

Figure 6. Dynamic IR Images Obtained with Vortex Coolers

III. Dynamic IR Modeling and Analysis

The focus of the modeling and analysis task was to provide analytical means to reduce the sensitivity of dynamic IR imaging to spurious thermal noise sources and to provide a quantitative measure of the sensitivity of dynamic IR imaging to the radiative thermal power of embedded sources. Several techniques were explored and the two most promising are presented below: the Karhunen Loéve (KL) transform and wavelet analysis. Of the two, the KL transform is the most rigorous and in the end would provide the most accurate characterization. We did not spend time optimizing the techniques, but rather investigated their general usefulness. We were able to show with wavelet analysis a direct correlation between power applied to the embedded heating cartridge and energy in the image that had been reconstructed using wavelet coefficients.

A. Karhunen Loéve transform

The Karhunen Loéve transform[1, 2] is used to extract spatial information in spatio-temporal systems. The technique has been applied in the study combustion and flame dynamics and other rapidly changing phenomena. Eigenvectors are generated from a time series of 2-D images. The principal decomposition using eigenvectors represents evolving spatial components. In our case, the spatial component of interest is the surface thermal gradient on the container due to the subsurface aluminum disk and heating element. Figure 7 shows the reconstructed images from the 2nd Eigenmode. Qualitatively the 0 and 4 watt images have similar spatial characteristics, as do the 8 and 12-watt images. When we did image energy calculations for regions around the disk, the 0 and 4 watt data was inseparable as was the 8 and 12-watt data, but the 0 and 4 watt images could be delineated from the 8 and 12-watt images.

B. Wavelet analysis

The strength of wavelet analysis is the ability to detect signals that are normally obscured by background clutter or noise. In our analysis we segmented the wavelet coefficients into groups representing image noise, bias signal, and the signature of interest. The image at the top of Figure 8 is the container thermal image that was reconstructed from the subset of coefficients representing the disk feature. In the graph we plot the image energy within the defined rectangle shown in the thermal image for each of the 3 cases: 0, 4, and 8 watts. The plotted lines represent respective energies in difference images (e.g., the image at 7 minutes into the test minus the image at 2 minutes) at various delta times (minutes) described in the graph legend. The plot shows a very strong correlation between the reconstructed images and heater power. Notice that the bottom trace is the set of raw images (no image subtraction) and shows no correlation between power applied to the heating element and image energy.

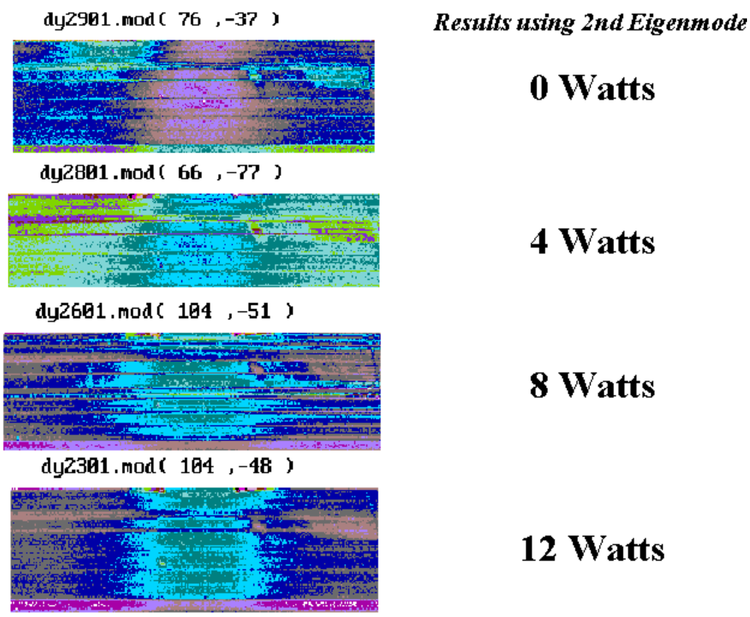

Figure 7. Karhunen Loeve Analysis of Dynamic IR Images

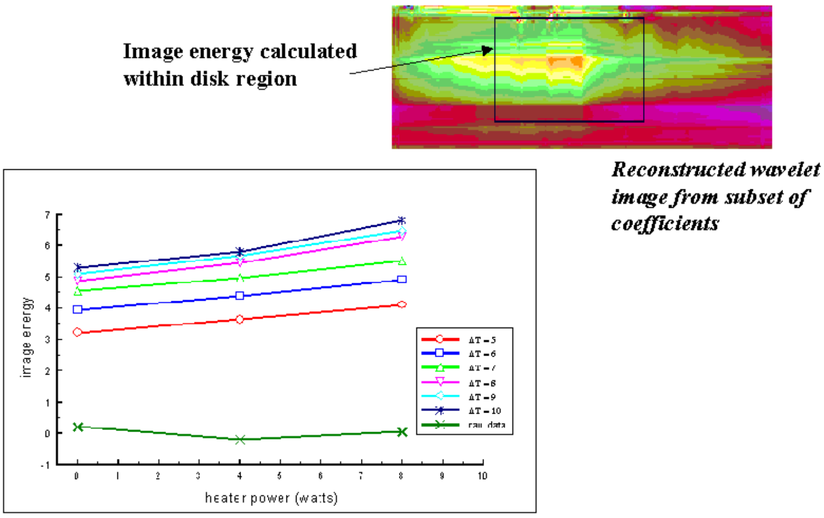

Figure 8. Wavelet Analysis of Dynamic IR Images

IV. Acoustic Tomography Inspection Technologies

Acoustic tomography is an alternative technology for imaging internal components of a container. Tomography is derived from the Greek "tomos" meaning slice and combined with "graphy" leads to the presentation of slice pictures or cross sections. Computerized tomography (CT) is the numerical reconstruction of cross-sectional pictures from their projections taken at various angles. CT has been used in the medical diagnostic field for many years with X-rays and ultrasonic waves. Acoustic energy can be easier and safer to use than ionizing radiation. In addition, the acoustic waves do not affect the media they pass through.

To provide information about internal components in a container, the acoustic energy must interact with those components. The primary interaction of a material with the acoustic energy is the material's acoustic impedance. This impedance is related to density of a material and secondarily to its compressibility at the frequency of the wave. The greater the difference of acoustic impedance at the interface of two materials, the greater the interaction. If the two materials have similar impedance, most of the acoustic energy is transmitted from one to the other. If the difference in impedance is significant, the percentage of energy reflected will be high. These reflections (interactions) can provide the basis for acoustic tomography. These ultrasonic interactions could include the attentuation of the amplitude of the acoustic wave due to absorption or scattering or the variation of the speed of sound due to inhomogeneous materials (air and solid interfaces).

The complete interaction between two materials is complex and depends upon the size and shape of the interface as well as their impedances. This leads to three types of acoustic tomography:

(1) transmission
(2) reflection, and
(3) diffraction.

To achieve a tomographic solution in 2-D and/or 3-D, data or slices from various viewpoints are required. The viewpoints or projections should be obtained by surrounding the area of interest with transmitters and detectors, preferably symmetrically. Typically, a transmitter and a detector (or a transceiver – transmitter and detector in one) are located across the region of interest from each other. A measurement is made and then both the transmitter and detector are rotated together around the region or the container would be rotated with the transmitter and receiver held fixed. This rotation produces the projections that are then combined together using a selected algorithm to produce the tomography view of the interior of the container.

If time to create an image is critical, the projections could be done in parallel or an array of acoustic transducers can be employed, removing the need to rotate either the container or the detector/transmitter pair.

A. Application to internal imaging of containers

A fan-shaped array of transmitters and receivers would most likely be used to produce the information for the acoustic tomography reconstruction of the internals of a container. Definition of the appropriate acoustic frequency, transducers, and reconstruction algorithms would experimentally be determined based on experience, the application, and experimental results.

The most likely measurement set-up would have acoustic transducers coupled to the outside wall of a container to be interrogated. Each of the transducers could be both a transmitter and a receiver and could be computer controlled to obtain projections across the container. In order to measure cross-sections of the container at different locations, the fan-shaped array would be placed at various positions along the container. The acoustic energy pulsing, detection, numerical reconstruction, and displaying of the results can be done by a single computer system.

The principle of operation is that the acoustic energy passes through the container wall to the interior. At a wall-air interface, almost all of the acoustic energy will be reflected (a large acoustic impedance difference). At a grid location, most of the energy will be transmitted to the interior components (solid to solid interface). The energy will be passed through the various interior components and to the wall at grid interfaces. Depending on the path lengths and number of interfaces, the signal intensity will vary.

The job of the numerical algorithm is to deconvolve these intensity signals into an image of the interior. To develop the appropriate algorithms, a physical model of the container system may be required. Simulations are run with the model to develop an understanding of the energy interactions and how those interactions determine the signal intensity at the various receiver locations. Determining the interactions and algorithms is not a trivial task.

The simulation can also be used to determine sensitivity and resolution expectations, and optimal sources/receivers number and locations. The sensitivity and resolution are important because the major purpose of imaging the internal components is to check for changes from a baseline image. Assuming this acoustic tomography functions well, checking for changes in the images from the baseline can be accomplished through "defect detection" algorithms that are used routinely in image processing work.

B. Experience at ORNL in computerized tomography

Oak Ridge National Laboratory has over 20 years of experience in CT using X-rays, gamma rays, and acoustic waves. Pioneering work has been done in developing acoustic tomography for locating underground features from environmental waste to dinosaur bones. Recently, researchers have invented technology for high-resolution CT for small animals. This technology, microCAT, allows rapid 3-D tomography at resolution of 100 microns or less. Along with the system to achieve the speed and resolution, algorithms have been developed to automatically look for changes in internal organs and structures in mice. This type of work can be directly applied to component imaging and change detection in containers.

V. Conclusions and Recommendations

ORNL has investigated the efficacy of alternative technologies to perform internal verification on containers. For dynamic IR inspection, we showed that by cooling the surface of a container and monitoring the surface heat flux, information about structures inside the container could be obtained. Not only were the general shapes of objects inside the container able to be imaged with an IR camera, but also information about the thermal radiance of embedded heat sources inside the container could be deduced. This technique thus has the potential for providing two independent parameters, internal structure and source power that could compliment information from other existing technologies. We also demonstrated the capability of performing these types of IR measurements using limited cooling in the form of vortex coolers. These coolers have no electrical requirements and use only instrument air to provide -20°C air at their exhaust port. A second possible technology for internal verification on containers is acoustic tomography. This technology has been used in a number of applications at ORNL including imaging underground features and imaging in small animal research.

VI. References

[1] Antonio Palacios, Gemunu H. Guaratne, Michael Gorman, and Kay A. Robbins, "Karhunen-Loève analysis of spatiotemporal flame patterns," PHYSICAL REVIEW E, Vol. 57, No. 5,1-14, May 1998.

[2] Richard A. Haddad and Thomas W. Parsons, “Digital Signal Processing Theory, Applications, and Hardware,” Computer Science Press, ISBN 0-7167-8206-5, 1991.