Dynamic IR Imaging of Nuclear Weapon Platforms for Treaty Verification

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ABSTRACT

The Defense Threat Reduction Agency's (DTRA) Arms Control Technology Division sponsored research at the Oak Ridge National Laboratory (ORNL) into the efficacy of infrared (IR) classification of full-up nuclear weapons as an alternative technology for treaty verification. In our effort, dynamic IR measurements were made on a BG61-11 weapon casing. 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 casing 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 weapons categorization.

INTRODUCTION

Normal infrared (IR) imaging uses the blackbody thermal emission from an object to characterize its surface temperature distribution remotely. 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

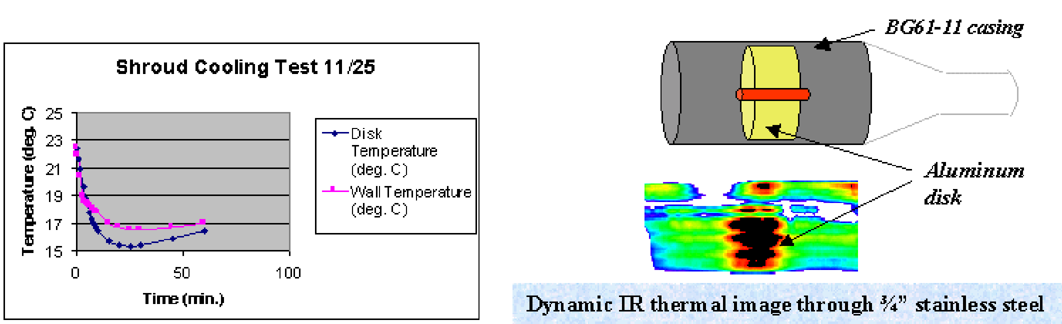

Figure 1. Initial Dynamic IR Experiments

resistive heating elements. In our tests, we experimented with various cooling methods, beginning with applying liquid nitrogen to the surface of the BG61-11 casing and later using commercially available vortex coolers. Even with liquid nitrogen cooling, the maximum temperature change inside the casing (as recorded with thermocouples) is only 6 to 7°C (see the cooling curves above).

Figure 1 above shows our experiment configuration for this project. An aluminum disk was inserted in a 2-cm. thick stainless steel BG61-11 weapon casing as shown. Embedded in the aluminum disk is a small cylindrical resistive heating element, simulating a thermal source inside a full-up weapon. The dynamic IR image in the figure, below the cartoon of the casing, 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 BG61-11 casing and provided a confined space for applying the liquid nitrogen. The shroud (see Figure 2 below) was developed to better control the cooling process by providing uniform cooling over a

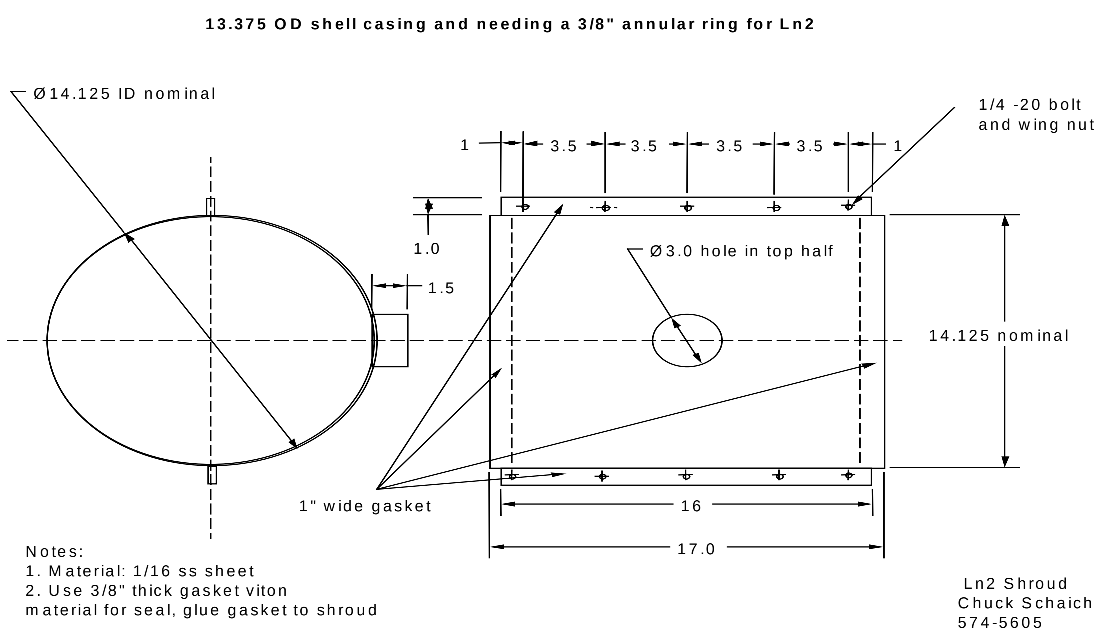

Figure 2. Liquid Nitrogen Cooling Test Ring

fixed time interval. During the tests, 4 liters of liquid nitrogen were poured into the shroud and the shroud was then removed after 1 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, for treaty verification, a less severe means of cooling is preferred. In a second set of tests, limited cooling was used on the

BG61-11 casing 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), see Figure 3 below. 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.

I. Experimental Results

A. Sensitivity to internal structure

One application of dynamic IR imaging involves the use of the technique to categorize nuclear weapons based on internal structure. Our initial tests were directed toward optimizing the imaging of the inserted aluminum disk through the 2-cm. stainless steel BG61-11 casing. In these tests, the BG61-11 casing was cooled using liquid nitrogen for a time interval of 1 minute. The external surface of the casing 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 below shows typical IR images of the casing at 7 and 9 minutes after the application of liquid nitrogen. The images were obtained by subtracting the frame taken at, for instance, 9 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.

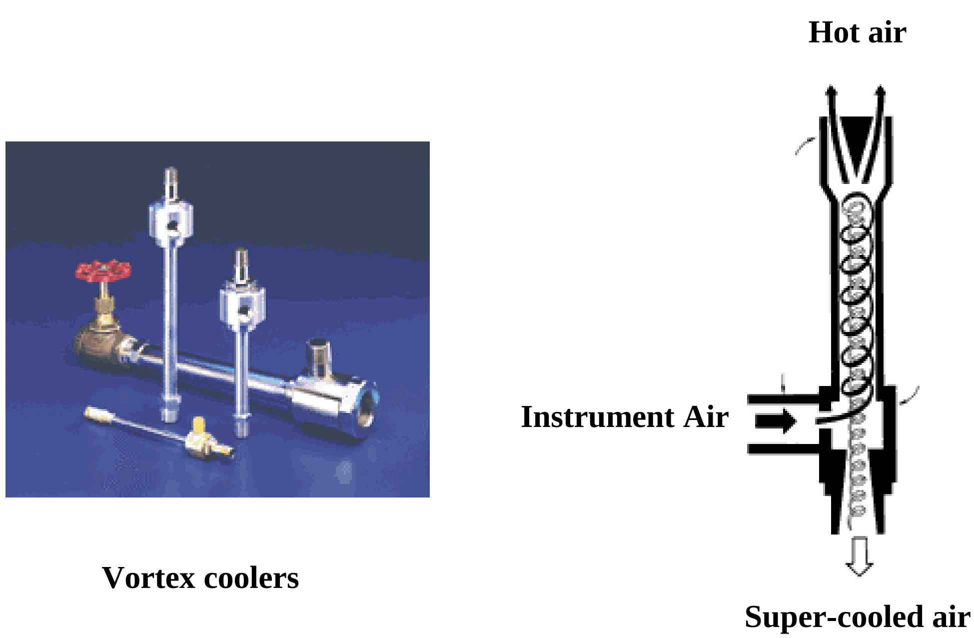

Figure 3. Vortex Coolers: Picture and Principle (reproduced with permission from ITW Vortec)

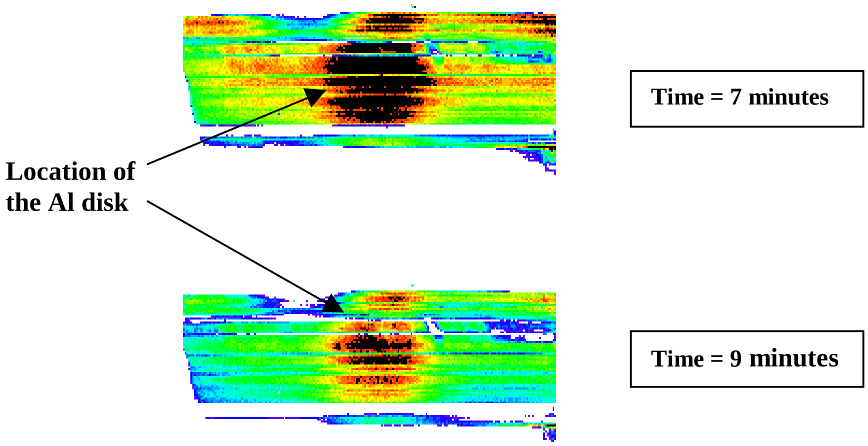

Figure 4. Imaging Internal Structure with Dynamic IR Techniques

B. Sensitivity to embedded heat source

A second piece of information needed for categorizing nuclear weapons for treaty verification is the presence of nuclear sources. We performed a series of tests with the BG61-11 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 BG61-11 stainless steel casing 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 casing 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 casing with disk reach equilibrium over a 24-hour period. We cooled the shell for 1 minute with liquid nitrogen and recorded a series of IR images of the surface of the casing 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 for treaty verification, an alternate cooling method to the liquid nitrogen is preferred and was investigated. We explored limited cooling of the BG61-11 casing 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

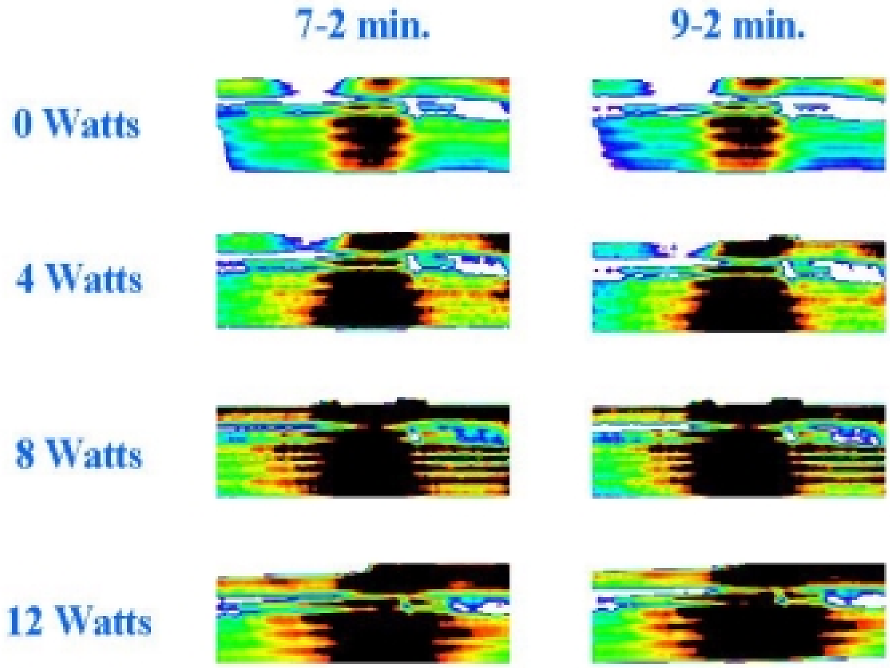

Figure 5. Sensitivity of Dynamic IR Imaging to Internal Heating Sources

through the shell. The resulting images are shown in Figure 6 below. 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 shell (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.

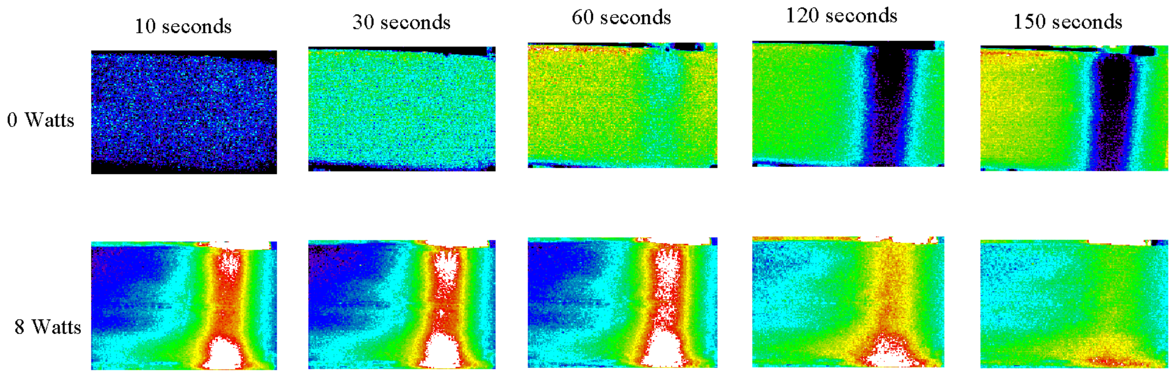

Figure 6. Dynamic IR Images Obtained With Vortex Coolers

II. 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 for categorizing weapon platforms. 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 BG61-11 shell 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.

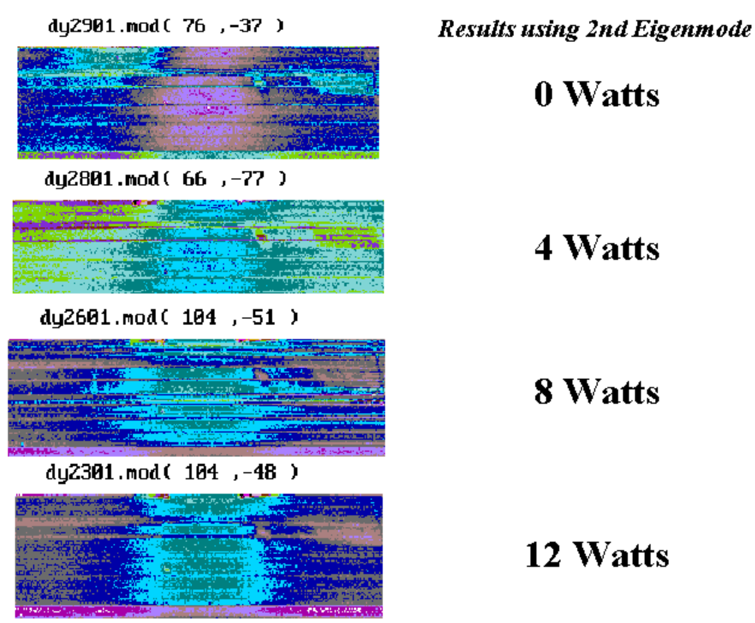

Figure 7. Karhunen Loéve Analysis of Dynamic IR Images

B. Wavelet analysis

The strength of wavelet analysis[3] 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 BG61-11 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.

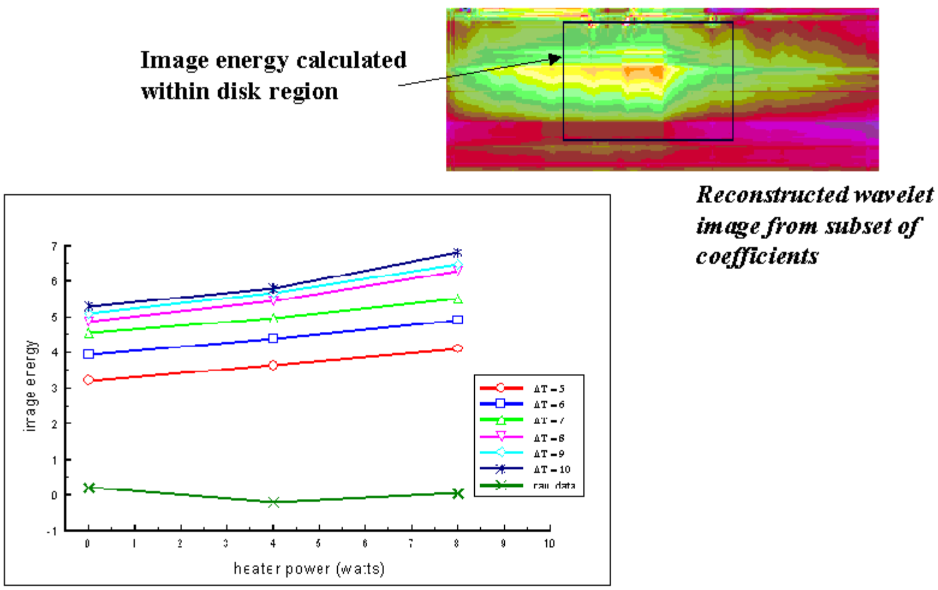

Figure 8. Wavelet Analysis of Dynamic IR Images

III. Conclusions and Recommendations

In this project, we investigated the efficacy of an alternative technology using a sensitive mid-wavelength IR camera to perform treaty verification on nuclear weapons platforms. We showed that by cooling the surface of a BG61-11 weapon casing and monitoring the surface heat flux, information about structures inside the casing could be obtained. Not only were the general shapes of objects inside the casing able to be imaged, but also information about the thermal radiance of embedded heat sources inside the casing 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 for weapons categorization. We also 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.

IV. References

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