$$_\lambda = \frac{2c^2h}{\lambda^5\left(e^{hc/\lambda kT}-1\right)}.$$

Optical Pyrometry on the Armando Subcritical Experiment

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Introduction

The Armando subcritical experiment (SCE) was the final shot in the Stallion series of SCEs, also consisting of two previous shots, Mario and Rocco. The primary objective of the Stallion series was to investigate differences in material properties between cast and wrought plutonium driven by high explosives (HE). The Armando experiment contained two plutonium/HE packages, which were identical except one contained wrought plutonium driven by high explosives (HE). The Armando experiment contained two plutonium/HE packages, which were identical except one contained wrought plutonium while the other held cast plutonium. The two packages were also identical to those fired on Mario and Rocco. While Mario and Rocco were primarily diagnosed using point techniques, Armando was primarily diagnosed using an area technique (radiography). However, two diagnostics were common to all three shots—a single-point velocimetry measurement using the velocity interferometer system for any reflector (VISAR) and optical pyrometry.

The optical-pyrometry technique measures the surface temperature of the plutonium as it is heated by the passage of the HE's shock wave. Light is emitted from an ideal blackbody surface based on its temperature in accordance with Planck's law:

(1)

Here L_λ is the radiance in W/m^2 sr m, c is the speed of light, h is Planck's constant, λ is the light's wavelength, k is Boltzmann's constant, and T is the temperature. In order to perform the measurement, a pyrometer is constructed using high-speed photomultiplier tubes (PMTs) filtered to be responsive to certain wavelength bands. Due to the explosive nature of the experiment, the pyrometer is located remotely from the package. An optical probe collects the light emitted from the plutonium surface and is sent over ~ 100 m of 1 mm diameter optical fiber. High-speed digitizers then capture the signals from the PMTs.

Pyrometry data was successfully returned from Mario, Rocco, and Armando. The data is currently being analyzed.

Pyrometer Design

The pyrometer system was specifically designed to meet the needs of the Stallion SCE series. In other words, the expected range of temperatures and the operating conditions of the overall experiment dictated the selection and layout of components. Armando required two identical pyrometers, one for each plutonium piece. One of our primary considerations was

Figure 1. Schematic diagram of the pyrometer.

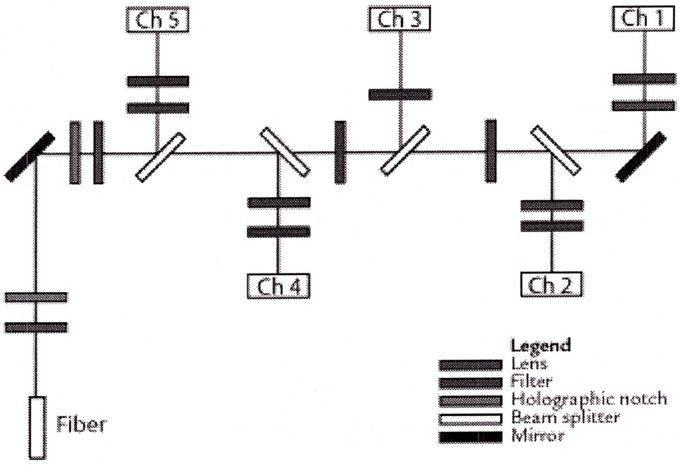


Table 1. Wavelength coverage of Armando pyrometers

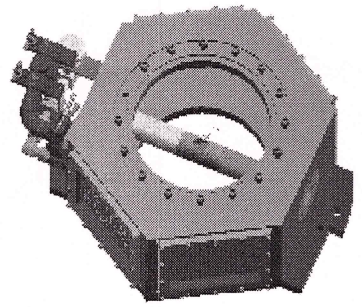
Channel	Spectral Range (nm)
1	1510–1670
2	1180–1300
3	800–900
4	690–750
5	496–517

measuring temperatures in the range of ~ 300 °C to ~ 1200 °C, to operate with timing resolution of a few ns, and to coexist with large quantities (many Watts) of 532 nm light from the VISAR lasers. Figure 1 illustrates the experiment's schematics and design. The pyrometer utilizes five channels, three in the visible spectrum and two in the near infrared. Each channel is a 2 in. diam PMT that has a ~ 3 ns rise time. The visible tubes are Hamamatsu R943-02 operating at room temperature, and the near-infrared tubes are Hamamatsu R5509-72 operating at -80 °C. Optical bandpass filters are placed in front of each tube to select a particular wavelength band, which are listed in Table 1.

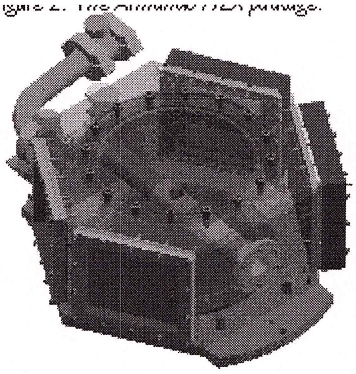
Referring to Figure 1, the operation of the pyrometer is as follows. First, light from the transporting optical fiber is brought into reasonable focus using a lens. The light then impinges on an OD6 holographic-notch filter which passes all light except those in a 10 nm wide band around 532 nm. The 532 nm light is reflected backward into a beam dump. The notation "OD6" indicates that the intensity of 532 nm light is reduced by a nominal factor of 106 in passing through the filter. After passing the first holographic-notch filter, the beam is bent 90° using a turning mirror. It then passes through a second OD6 holographic-notch filter for a total reduction of 532 nm light of up to 12 orders of magnitude. The beam then passes through a lens to further adjust the focus before proceeding through a series of dichroic beam splitters. Each beam splitter reflects wavelengths shorter than a cutoff value into the PMT designated to measure a corresponding wavelength band. Each PMT also has a lens in front of it to focus the incident light for optimal geometric coverage of its photocathode. A passband filter is also used with each channel to define the wavelength coverage. The longest wavelengths are sent to channel 1 using a turning mirror instead of a beam splitter.

Armando Experiment Design

igure 3. The Armando HEX package
howing the location of the mirror in the
enter of the combined pyrometer/
SAR probe tube.



igure 2. The Armando HEX package.



The Armando experimental package was designed to allow for simultaneous firing of two plutonium/HE subassemblies, identical except for the initial plutonium shaping technique. These two subassemblies were mounted on the top and bottom of a six-sided (HEX) package (Figure 2). Two radiographic lines of sight, spaced 60° apart, were aligned with four of the six package sides. A tube was mounted through the remaining two sides of the package. At the center of the tube, a double-sided mirror was mounted at a 45° angle to the axis of the tube such that the upper plutonium surface could be viewed through one end of the tube and the lower plutonium surface could be viewed through the opposite end of the tube (Figure 3). The tube had to be made small, so that the two radiographic images could be obtained before the plutonium surface impacted the tube.

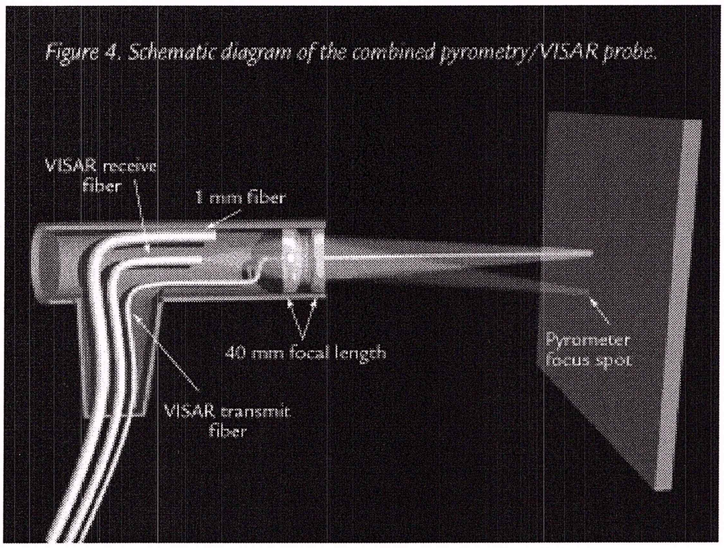


Figure 4. Schematic diagram of the combined pyrometry/VISAR probe.

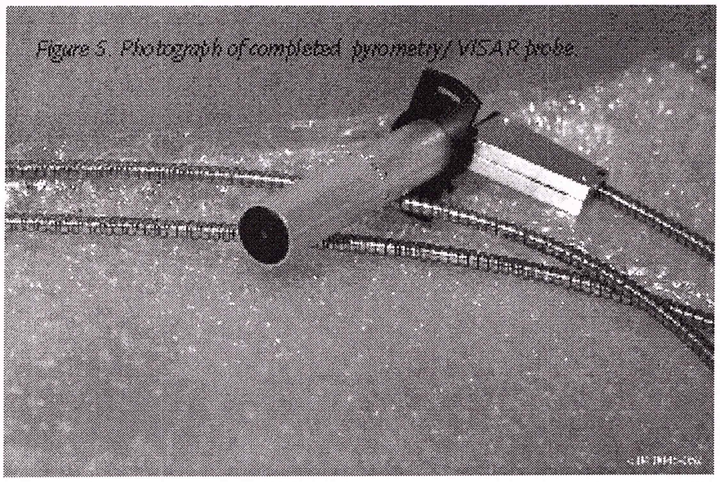
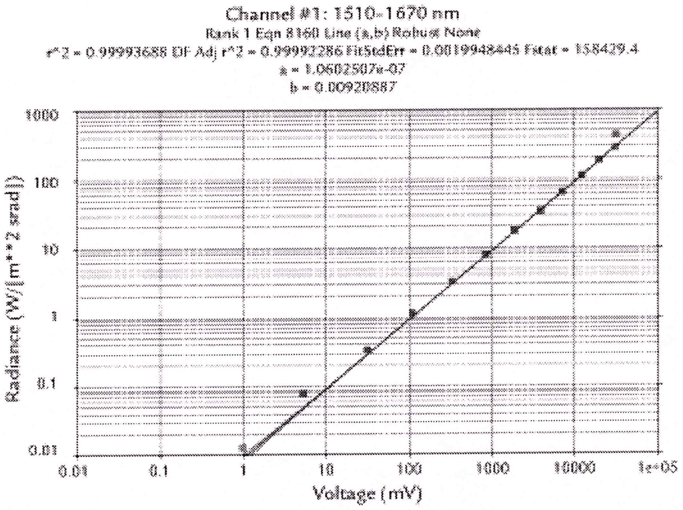


Figure 5. Photograph of completed pyrometry/VISAR probe.

The central tube provided optical access for the pyrometry and VISAR diagnostics. Our colleagues at Bechtel Nevada (BN) did an outstanding job at designing an integrated optical probe, incorporating the needs of both the pyrometry and VISAR teams. The VISAR transmit fiber was mounted in a small hole drilled through the center of the two lenses which were mounted at the front of the probe. Return light for the VISAR was then focused on a receive fiber mounted behind the transmit fiber. The larger, 1 mm diameter, pyrometry fiber was mounted off-axis to the probe so that it received light from a spot on the plutonium surface approximately 1 cm away from the spot illuminated by the VISAR laser. This scheme is illustrated in Figure 4. A photograph of a completed probe is shown in Figure 5. One probe was inserted in each side of the hex package central tube.

$$_i(\lambda, T) = \int_{\Delta\lambda_i} \varepsilon_i L_\lambda d\lambda,$$

Figure 6. Example calibration data.



Pyrometer Operation

Before the experiment, each pyrometer must first be calibrated with a blackbody source to obtain the relationship between measured output voltage on the PMTs and the incident radiance. The procedure is to set the blackbody at a specified temperature and measure the output voltage on each PMT. The radiance for each channel can then be calculated by

(2)

where L_λ is as before and ε_i is the emissivity. For a blackbody, the emissivity is unity and the radiance is easily calculated using the known bandpass characteristics of each filter. An example of the resulting calibration data is shown in Figure 6. Note that the PMTs are linear from a few mV to a few tens of volts. We performed these calibrations using the complete optical system, including pyrometer, fiber, optical head, and hex package tube and mirror. In the experiment, we measure a voltage, which has a corresponding radiance $L_i(\lambda,T)$, for each pyrometer channel. However, unlike in the calibration case, we do not know the emissivity of the plutonium surface. Hence, we have N measurements but N+1 unknowns, corresponding to the N unknown dynamic emissivities plus the temperature. In order to address this difficulty, we make two assumptions:

1. the radiances all correspond to a single temperature, even though the dynamic emissivities may be different (emissivity is in general wavelength dependent) and

2. that the dynamic emissivity can be bound using known properties of the material.

For example, the emissivity must have an upper bound of 1, corresponding to that of a blackbody. A reasonable lower bound might be the static emissivity of a freshly machined or polished surface. With these assumptions an additional 2*N* of constraints are introduced, allowing a temperature (and associated uncertainty) to be derived. Note that due to the shape of the radiance curve, the shorter wavelength channels most strongly constrain the temperature.

Armando was successfully fired on May 25, 2004. Pyrometry data was returned on all channels, and the analysis of the data is ongoing. However, our preliminary analysis clearly shows measurable differences in the radiance from the cast and wrought parts—in a manner similar to that observed between Mario and Rocco.

Acknowledgment

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