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HEAT FLUX AND INFRARED SPECTRAL MEASUREMENTS OF BURNING SRM PROPELLANT (PREPRINT)

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1.0 ABSTRACT

On 23 August 2005 the Air Force Research Laboratory (AFRL) Propulsion Directorate at Edwards AFB conducted an open air burn of over 2000 kg of Titan IV solid rocket motor propellant. Multiple remote sensors were deployed to measure the heat flux and spectral emissions during the burn. The heat flux data was utilized to help determine the hazard classification for the propellant. An average normalized irradiance of 1.62 kW/m^2 was obtained during a nominal portion of the burn and supports a classification of 1.4. A Fourier Transform Infrared (FTIR) spectrometer collected data over a spectral range of $1.4 - 14 \text{ }\mu\text{m}$. Those data show strong gaseous emissions from carbon dioxide, water, and hydrogen chloride as well as a continuum emission component due to the aluminum oxide particulates.

2.0 INTRODUCTION

On 23 August 2005 the Air Force Research Laboratory (AFRL) Propulsion Directorate conducted a large scale open air burn of solid rocket motor propellant. The AFRL motors branch (PRSM) used the burn as an opportunity to collect heat flux data to support ongoing motor development programs. Locally available heat flux transducers and a Fourier Transform Infrared Spectrometer (FTIR) were successfully deployed to the burn site for the measurement. A group from Sandia National Laboratory also collected heat flux, visible video, infrared imagery, and infrared spectra during the burn. While this report only summarizes the AFRL results, the Sandia visible video data was used to identify and correlate the various temporal events.

The primary purpose for the effort was to measure the heat flux and compare to industry accepted values that identify the appropriate propellant hazard classification. The heat flux transducers were considered the primary instruments with the spectrometer as support and also providing additional analysis capability if necessary. Sample data sets are shown along with an initial assessment of the hazard classification for the propellant.

A picture of the propellant stack is shown in Figure 1. It is approximately 1.52 m in diameter and 0.66 m in height. The picture shows a separate thin (10 cm) slab on top of a single much thicker piece. The total propellant weight is 2083 kg. The propellant is highly aluminized (19%) and was inhibited on the sides with a mixture of HTPB, carbon black, and titanium dioxide.¹



Figure 1. Propellant Stack Just Before Burning

3.0. INSTRUMENT SPECIFICATIONS

3.1 Transducers

A total of four Medtherm heat flux transducers were used during the burn. Two of the transducers were purchased specifically for the measurement while the other two were borrowed from a recently completed rocket engine test. The two new transducers ranges were based upon pre-burn estimates. They respond to heat fluxes from 0 to 50 kW/m². The two additional transducers responded to heat fluxes from 0 to 454 kW/m² and were included in case unknown factors resulted in much higher signals than estimated. While the signal estimates were as expected, some unexpected propellant burning events did occur and including the high range transducers turned out to be useful.

3.2 FTIR Spectrometer

The FTIR spectrometer measures the infrared emissions with two simultaneous detectors, a Mercury Cadmium Telluride (MCT) and an Indium Antimonide (InSb). The MCT has a spectral range of approximately 2 – 18 μm while the InSb range is nominally from 1 – 6 μm . The spectrometer was located approximately 445 m from the propellant stack. Emissions were measured at two different spectral resolutions and frame rates at separate time periods during the burn: Approximately 10 Hz and 1 cm⁻¹ and at 34 Hz with a 4 cm⁻¹ resolution. The instrument was calibrated via a collimated blackbody source at two temperatures. At the stack, the IR field of view (FOV) was approximately 8 m full-width half-max (FWHM).

4.0. GENERAL EXPERIMENT SUMMARY

4.1 Propellant Burn Summary

Visible video of the propellant burn was obtained by both AFRL and Sandia National Laboratories (SNL).² One of the SNL video cameras provided a wide field of view and was quite useful for correlating temporal events to the transducer data. The video shows a nominal ignition and initially, burning only from the top surface as expected. Approximately 9 sec into the burn though, hot gas is observed escaping between the two slabs of propellant. Shortly thereafter what's left of the upper slab is levitated and slides off the stack onto the ground causing a much larger and more expansive conflagration. Then after a few more seconds some of the burning propellant moves into the vicinity of one pair of transducers. For a short period of time those transducers were engulfed in burning propellant. Once all of the pieces of the upper slab burn up (~ 42 sec from ignition), the burning lower slab is again observable. It burned fairly steadily to completion but with all exposed surfaces burning. All burning was complete in a little over 3 minutes from ignition.

4.2 Transducer Measurement

The transducers (one high range and one low range) were mounted in pairs on two tripods. Figure 2 shows two of transducers mounted on a tripod just before the measurement. The tripods were setup to be 15 m from the most likely propellant final position. Unfortunately, the final propellant placement resulted in distances of approximately 11.7 and 22.2 m. The viewing angle between the tripods was approximately 90° . The transducers were raised to a height of approximately 1.6 m and pointed roughly horizontal to the ground to capture the expected primary burning region. Transducer output voltages were recorded by a single LeCroy Oscilloscope located inside a small building near the burn site. Standard BNC cables were used to connect the transducers.



Figure 2. Transducer Pair Just Before the Burn

Figure 3 shows the raw voltage data from all of the transducers in time. As is clearly observed there is substantial variation in the heat flux over the burn time. From approximately 4 – 10 sec the propellant appears to be burning nominally. The first increase correlates to the time when the upper slab floated off the propellant stack and caused the large conflagration. The substantial increase near 25 sec occurred when a portion of the burning propellant from the top slab engulfed the short range transducers. The low range transducer clearly saturated but the high range still gave a good reading. Since neither the visible video or heat flux data were time stamped, exact temporal correlations to the visible video were difficult. After the large conflagration was over, a steadier burn was observed from all the sensors. This correlated well with the Sandia video over that same time period. The data cutoffs resulted from heat damage to the BNC cabling.

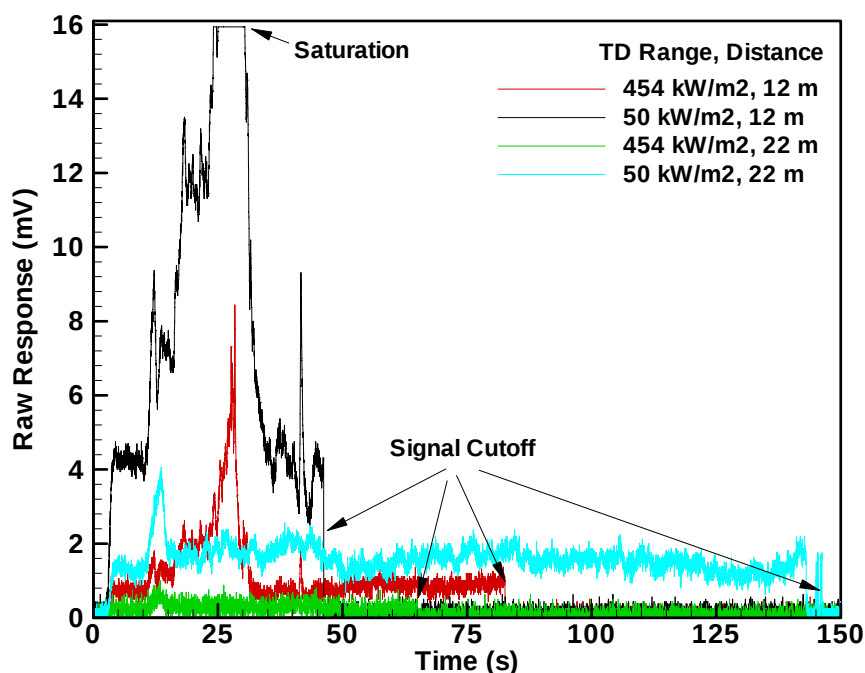


Figure 3. Transducer Raw Voltages in Time

4.3 Spectrometer Measurement

The spectrometer was located near the control building so it could be operated by computer via a fiber optic link. Figure 4 shows a visible image at the start of the burn. The object just to the right of the propellant stack is an old iron structure. It is actually on the left but the telescope optics reversed the image. The stack itself is actually some distance behind the iron structure as well. The iron girders for the tower are just visible behind the propellant. Unfortunately, most of the video was saturated as the camera was not stopped down enough.

Since the propellant was expected to burn 8 – 10 minutes, multiple data collections were planned at different spectral resolutions. In the end, due to the short burn only two data sets were collected. Figure 5 shows the integrated temporal profile of the two data sets. The times shown are from the instrument start time of each measurement. Due to an initial sensor saturation problem the first data (1 cm^{-1}) set was not collected until nearly 60 sec into the burn. At that time though, the propellant stack was burning fairly steadily. The second data set (4 cm^{-1}) was

collected close to the end of the burn as evidenced by the rapidly decreasing intensity. Again, accurate time correlations could not be made since the transducer data was not time stamped.



Figure 4. FTIR Spectrometer View of Propellant Burn Area

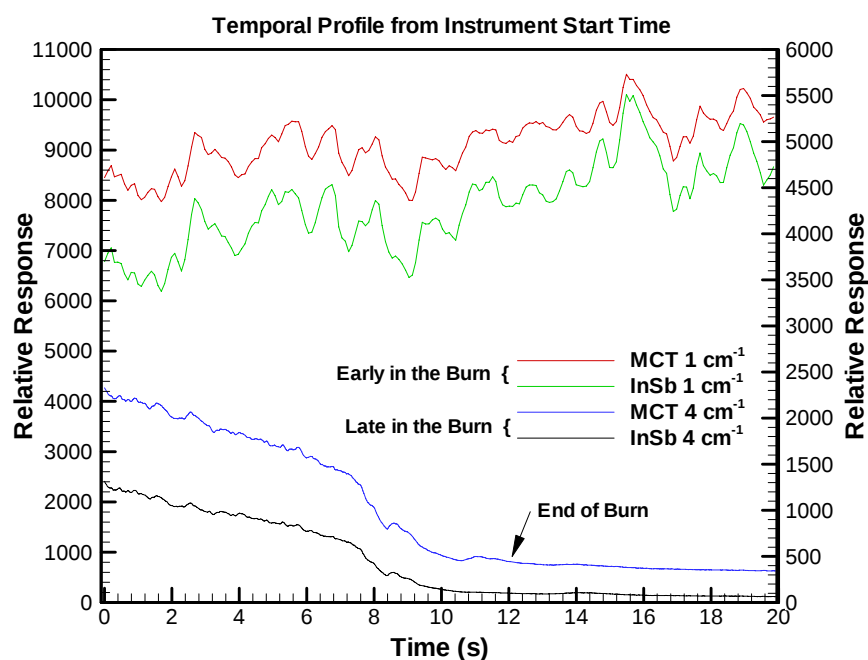


Figure 5. Integrated Relative Response from the FTIR Spectrometer

Relative spectral intensities from the MCT detector are shown in Figure 6. The spectrums were generated from a single frame of data from each of the collects. Various gaseous spectral emission features are noted such as hot water, carbon dioxide, and hydrogen chloride. Absorption due to carbon dioxide and water in the atmosphere are also shown in the plot. Also noted is an underlying continuum emission curve from the hot aluminum oxide particulates. These are typically found in solid propellant rocket exhaust emissions.

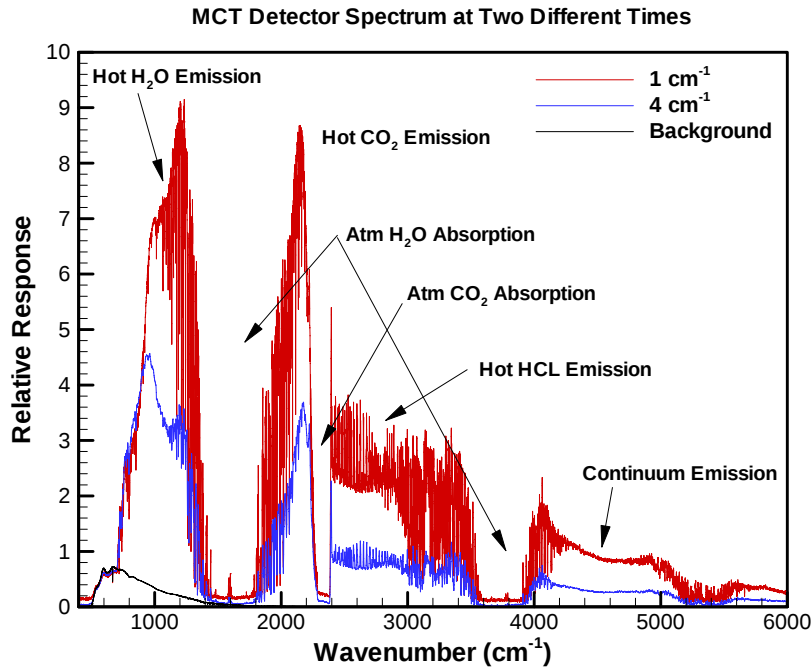


Figure 6. FTIR Spectrometer Relative Spectral Intensities

5.0 DATA ANALYSIS AND CORRELATIONS

5.1 Transducer Results

The transducer data were converted from voltages to apparent irradiance using the manufacturer calibration curves. Figure 7 shows the reduced data with time. Each pair of sensors recorded essentially the same irradiance but with varying noise levels. According to the manufacturer the uncertainty in the measurement is 3% of the value. To verify the hazard classification, each measurement was then normalized to a standard 15 m range and 100 kg mass. The equation used in the conversion was

$$I \propto \frac{m^{2/3}}{r^2}, \quad (1)$$

where I is the irradiance, m is the propellant mass, and r is the range.³ Figure 8 shows the normalized data in time. This time all the heat flux sensors data provide nearly identical values over steady state portions of the burn. The steady state portion of the burn from approximately 4 – 10 sec appears to be representative of the nominal burn profile. From that an average normalized irradiance of approximately 1.62 kW/m² can be used for comparison to the standard

hazard classification. The transducer manufacturer cites a 3% uncertainty in the irradiance calibration which places an upper bound of no more than 1.7 kW/m^2 . The portion of the burn from 35 – 85 sec, while also a steady state, included burning from the sides of the stack and is therefore compromised. The short range transducers also record a couple of increases to new steady state values at approximately 12 – 16 and 18 – 23 sec. These appear to correlate with the propellant movement toward the transducers from the video and also would not be considered valid points for comparison. The figure shows the long range transducer initially matches the short range transducers intensity profile. It then departs near 12 sec increasing to nearly 5 kW/m^2 before returning to approximately 2 kW/m^2 a few seconds later. At various times during the burn, smoke may be blocking the emission in different directions resulting in the differing temporal nature of each transducer pair. The fact that they all match initially and even at a much later time after the large variations, supports 1.62 kW/m^2 as a nominal value for comparison to the hazard classification standard.

5.2 Spectrometer Results

As mentioned earlier, only the 1st spectrometer data set was collected during a steady state portion of the burn. Frames of data from approximately 2.5 – 8.4 sec in Figure 5 were co-added and converted to spectral intensities with wavelength. The results from both detectors are shown in Figure 9. The conversion was accomplished by generating a calibration curve from measurements of a collimated blackbody source at temperatures of 700 and 1000°C . The InSb data extend down to $1.5 \mu\text{m}$ and the MCT data extend out to $14 \mu\text{m}$. Ideally the two spectra should be identical in magnitude but due to slightly different FOV's and detector response nonlinearities there is usually some difference. This comparison is considered good.

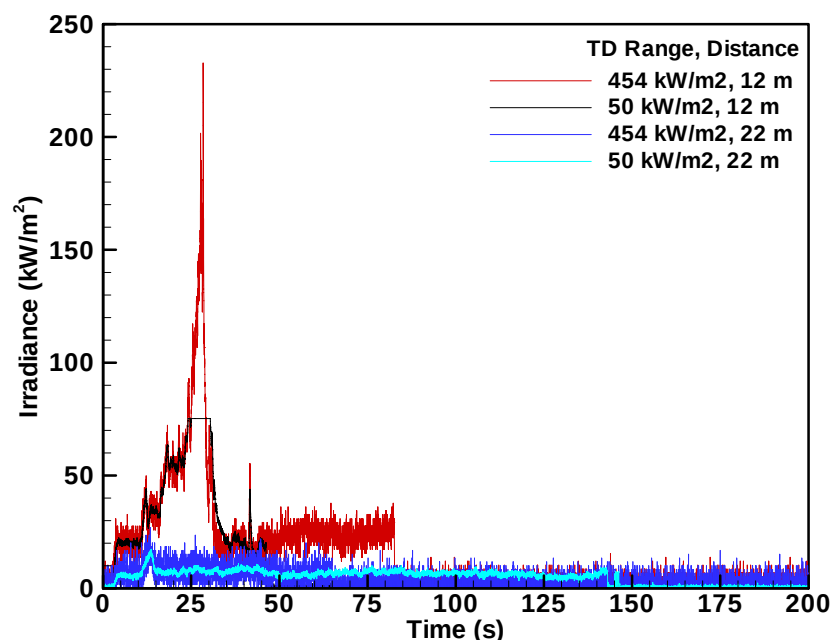


Figure 7. Measured Transducer Irradiances

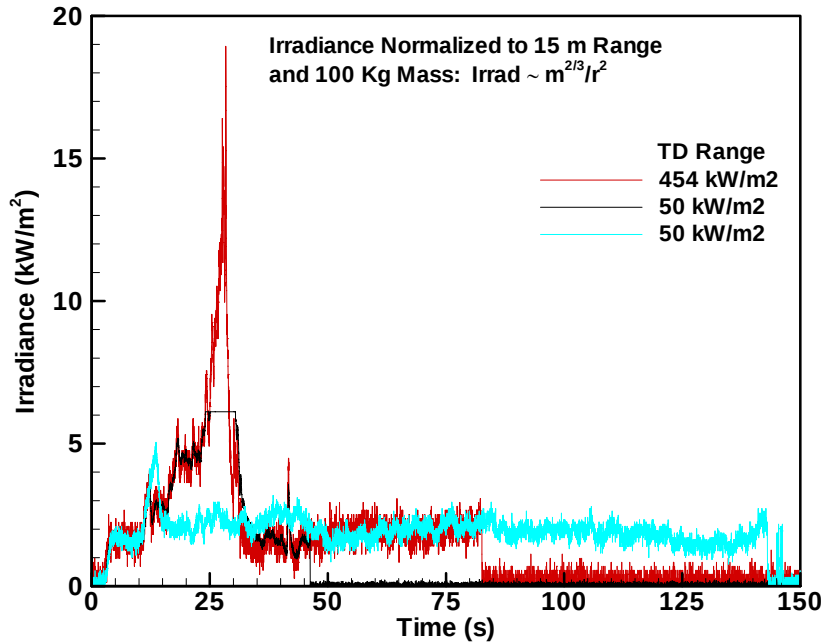


Figure 8. Normalized Transducer Irradiance

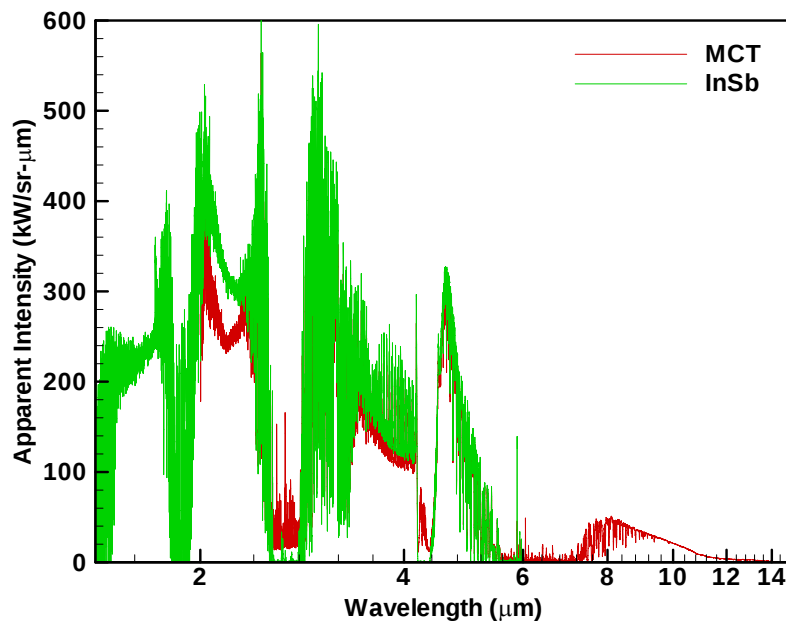


Figure 9. Apparent Spectral Intensities from the InSb and MCT Detectors

The wide spectral coverage allows a possible direct comparison with the transducer data. Even though the spectrometer data was collected nearly 60 sec into the burn, the transducer data show an approximately equivalent value at that time to the nominal burn data at 4 – 10 sec. The transducer is ideally responsive to all wavelengths and would thus include the visible and near infrared regions of the spectrum. Depending on the overall flame temperature, emission in these regions could be a substantial component of that recorded by the transducers. Nonetheless, it was expected the emission recorded by the spectrometer, when integrated, should be approximately $\frac{1}{4}$ to $\frac{1}{2}$ that measured by the transducers. To complete a comparison, the

spectrometer data was corrected for atmospheric absorption and normalized to 15 m using Equation 1 as well. Figure 10 shows the spectral irradiance from a combined (MCT/InSb) spectrum at 445 m range with that normalized to a 100 kg mass at 15 m range. The normalized data curve is approximately two orders of magnitude higher than the irradiance at the FTIR position. This is due primarily to the r-squared dependence of the intensity. The strong underlying continuum emission from the aluminum oxide particles is very apparent in the plot.

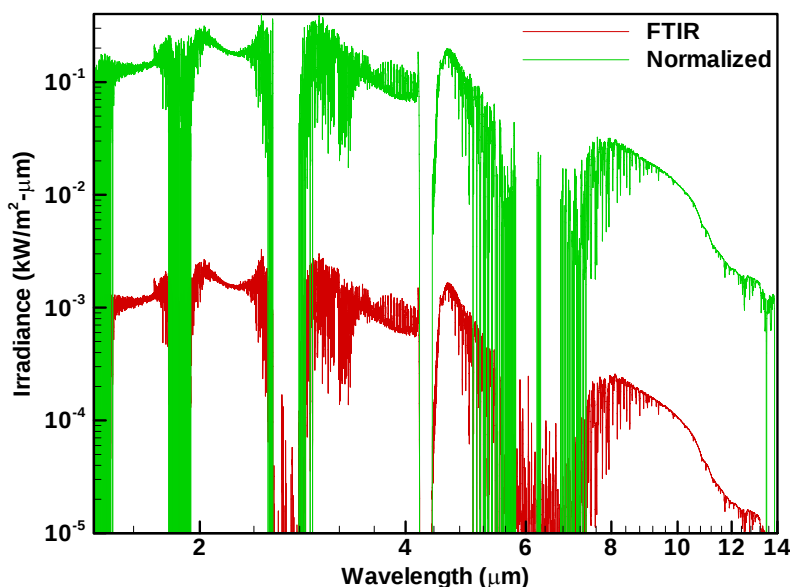


Figure 10. Spectral Irradiance at Spectrometer and Normalized to 15 m and 100 kg mass

Integration over the entire normalized curve in Figure 10 yielded a value of 0.52 kW/m^2 . This is approximately $1/3$ of that obtained from the transducers during the steady state burn and is consistent with expectations. From the slope of the curve below $2 \mu\text{m}$ in Figure 10 it does appear there would be significant additional irradiance in the visible and NIR spectral regions. Also, not all of the atmospheric absorption can be corrected, again leading to a smaller value than that measured by the transducers. There may have also been some blockage of the flame region by the aforementioned iron structure which may be contributing to the difference as well.

6.0 SUMMARY AND CONCLUSIONS

A measurement of the radiant thermal flux during the propellant burn was generally successful. Both the transducers and spectrometer collected useful data over at least part of the burn. The reduced and normalized transducer data generally overlapped during the quiescent portions of the burn. Those data show a normalized (to 15 m range and 100 kg mass) average radiant flux of 1.62 kW/m^2 . This supports a hazard classification of class 1.4 for the propellant since it is not above 4 kW/m^2 .⁴ The integrated normalized spectrometer data was approximately $1/3$ that measured by the transducers. This is considered a reasonable comparison due to loss from the spectrometer's limited spectral range, atmospheric absorption, and potentially some physical blockage.

6.0 ACKNOWLEDGEMENTS

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