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Infrared Signatures of the Muzzle Flash of a 120 mm Tank Gun and their Implications for the Kinetic Energy Active Protection System (KEAPS)

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Infrared Signatures of the Muzzle Flash of a 120 mm Tank Gun and their Implications for the Kinetic Energy Active Protection System (KEAPS)

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Sensors and Electron Devices Directorate

Abstract

This report examines the results of infrared (IR) imaging of the firing of M865 kinetic energy (KE) rounds from a 120-mm tank gun in support of the Kinetic Energy Active Protection System (KEAPS) development. The primary objective was to determine the extent in time, space, and intensity of the muzzle flash in both the 3 to 5 μm (medium-wavelength IR or MWIR) and 8 to 12 μm (long-wavelength IR or LWIR) wavelength bands. The secondary objective was to determine whether or not the IR cameras could detect the KE rounds and/or their sabots and to what extent the sabots could cause false targets for a prospective active protection system. Results showed that the brightest parts of the muzzle flash extended up to 10 m on either side of the gun and that the intensity of the flash was enough to saturate the imagery for more than 0.5 s in each wavelength band. Additionally, the MWIR camera was essentially blinded for several frames soon after the gun was fired while the LWIR camera was able to provide high fidelity imagery for the entire duration of the flash. In addition, the LWIR camera was able to detect the KE round and the sabots consistently.

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1. Introduction

One of the greatest threats to armored vehicles in the field is high-speed kinetic energy (KE) penetration rounds. These rounds are typically long, narrow rods composed of depleted uranium (DU) that are launched at speeds over 1500 m/s. The object of the Kinetic Energy Active Protection System (KEAPS) is to protect a vehicle that has been fired upon by an enemy KE round (in addition to high-explosive rounds) by detecting, tracking, and deflecting or destroying the incoming round. To accomplish its mission, the KEAPS must be able to detect and track the round from the time it is launched until just before impact. The speed of the projectile and the angle at which it approaches its target make this a very challenging task. It is expected that in the final configuration of the active protection system, sensors covering a wide range of the electromagnetic spectrum will be employed. An important sensor component will be an infrared (IR) camera that will be able to detect the thermal signature of the incoming round. It is well known that KE rounds become hot and that they present a considerable IR signature. It is also well known that the guns that fire KE rounds have a considerable muzzle flash. The precise signature of the muzzle flash, as seen head on, has not been measured in the IR and other spectral wavelengths. It is possible that the IR signature of the muzzle flash is of a sufficient extent in space and time to mask the signature of the KE round until impact is imminent. If that is the case, then it will be difficult if not impossible to use an IR camera effectively to track the incoming round and cue the countermunition.

To satisfy the need for data on the signature of the muzzle flash, a field data collection was held in March 2000 at the Transonic Experimental Facility at the Aberdeen Proving Ground, MD. Personnel from the Weapons and Materials Research Directorate (WMRD) of the U.S. Army Research Laboratory (ARL) arranged and directed the test. During this field test several M865 KE rounds were fired from a 120-mm tank gun. These firings were observed by a number of sensors covering the ultraviolet (UV) through the IR. This report presents the results obtained by the IR cameras covering the 3 to 5 μm and 8 to 10 μm (also known as medium-wavelength IR or MWIR and long-wavelength IR or LWIR, respectively) wavelength ranges, that were brought to the test by personnel from the Sensors and Electron Devices Directorate (SEDD) of ARL.

2. Experiment

2.1 IR Cameras

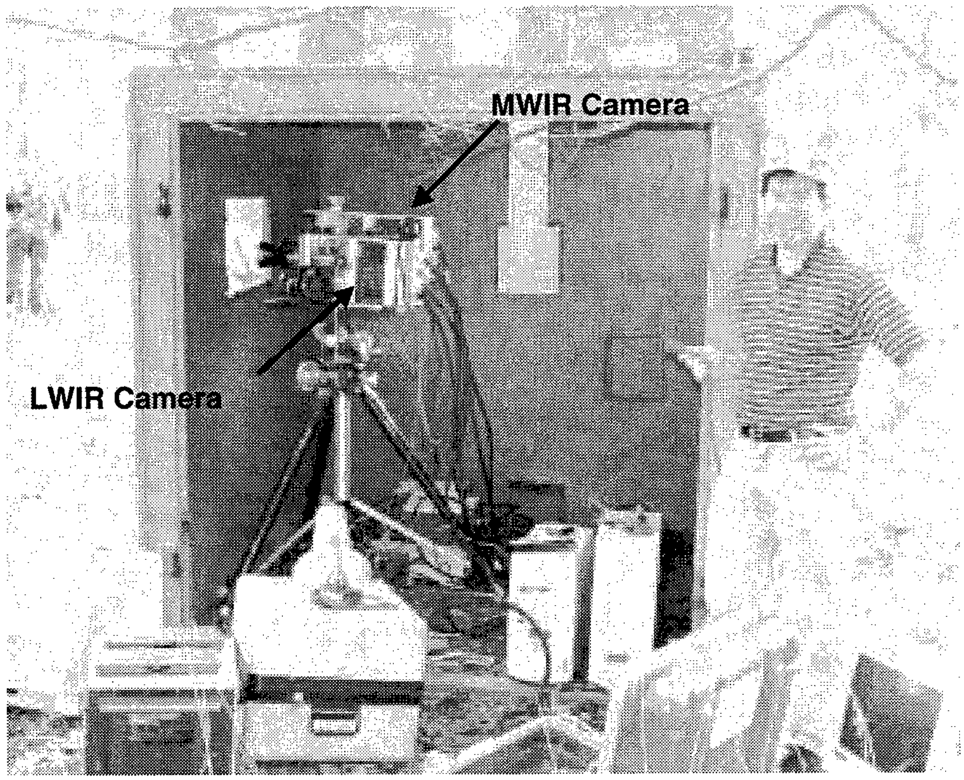
The specifications for the cameras used in this field data collection are shown in table 1 below. The two cameras had identical formats, pixel sizes, and optics that gave them identical instantaneous fields of view (IFOV). A photograph of the two cameras inside the armored camera box is shown in figure 1.

Table 1. Properties of the infrared cameras.

Property	MWIR	LWIR
Detector material	InSb	GaAs/AlGaAs
Detector type	Photovoltaic	Photoconductive QWIP
Operating temperature	77 K	65 K
Wavelength range	2.0–5.3 µm	8.0–10 µm
Array format	512 × 480*	512 × 480*
Pixel size	24 µm	24 µm
Imaging optics	100-mm focal length, f/2.3	100-mm focal length, f/2.3
IFOV	0.24 mrad	0.24 mrad
Total field of view	7.04° × 6.60°	7.04° × 6.60°
Integration time	0.26 ms	0.48 ms
Frame rate	45.0 Hz	49.8 Hz†
Sensitivity (NEΔT)	0.025 °C	0.032 °C
Dynamic range	12 bits	12 bits

*Acquired array window, full array format was 640 × 480 pixels.
†The FPA was run at 49.8 Hz; image data was acquired at 25 Hz.

Figure 1. LWIR and MWIR cameras inside armored camera box.



A pulse from the gun-firing mechanism that was set to start the data acquisition 50 ms before the gun fired triggered the cameras. This insured that there would be at least two frames captured before the beginning of the flash. Each camera was set to record 62 consecutive frames of digital imagery. In an attempt to record imagery in both wavebands over the same period of time, the cameras were run at as close to the same frame rate as possible. However, after processing the image data it was found that the LWIR camera's framegrabber recorded at half the actual frame rate. The recorded LWIR imagery spanned 2.44 s (62 frames at 25 frames/s). The data from the MWIR camera was recorded at the actual 45 Hz frame rate. Therefore, the 62 frames of MWIR data spanned 1.36 s in real time. The cause of the failure to record the LWIR data at the actual frame rate is thought to be due to the relatively short time between the last active pixel of one frame and the first active pixel of the next frame in this particular focal plane array (FPA). The framegrabber used in these camera systems is only able to sense the frame clock of the LWIR FPA on every other frame in this timing scheme.

2.2 Shots

There were a total of eight rounds fired from the 120-mm gun over a 3-day period. For the first two shots, the cameras were placed in an armor-plated box 100 m from the gun and about 3 m perpendicular to the shot line. For the succeeding six shots, the cameras were moved to an armor-plated box 260 m from the gun and 20 m perpendicular to the shot line. There were several instances in which one or both of the cameras did not record any imagery. Table 2 shows a summary of the shots fired and the data that was acquired from each of the cameras.

The cameras were moved 260 m from the gun for two reasons:

1. Initial analysis of the data from the first two shots indicated that the extent of the muzzle flash was nearly as large as the camera's field of view.
2. The large amount of ground vibration present at 100 m from the gun was the cause of the lockup failures observed of the MWIR camera's computer.

Most of the following analysis was taken from only two of the eight shots (shots 4 and 5) because these were the only shots that both cameras recorded properly triggered digital imagery.

Table 2. Data captured for each of the shots.

Shot	Date	Range	MWIR	LWIR	Explanation
1	March 9	100 m	No data	Yes–60 frames	MWIR computer failure
2	March 9	100 m	No data	Yes–60 frames	MWIR computer failure
3	March 13	260 m	No data	Yes–60 frames	MWIR camera not operational
4	March 13	260 m	Yes–62 frames	Yes–62 frames	—
5	March 13	260 m	Yes–62 frames	Yes–62 frames	—
6	March 14	260 m	No data	No data	Trigger failure
7	March 14	260 m	No data	No data	Trigger failure
8	March 14	260 m	S-VHS analog video	Yes–62 frames	MWIR trigger failure

3. Analysis and Discussion

3.1 Shots at 100 m Range

Figure 2 shows the frame of LWIR imagery just preceding ignition of the shot and the following five frames. In the first frame recorded after the ignition of the gun (within 40 ms of the actual ignition time), the saturated part of the image is approximately 290 pixels wide. Given that the IFOV of the camera was 0.24 mrad and that the gun was 100 m from the camera, I can estimate that the width of the flash at the target was approximately 7 m at that time. After four more frames (200 ms after the blast), the width of the flash was 420 pixels corresponding to a ground extent of just over 10 m.

Figure 3 shows an "image" of the pixel intensity as a function of column number and time (frame number) for a particular row of the FPA. The brightest part of the muzzle flash extends to nearly the entire width of the scene in less than 400 ms. This implies a width of the flash at the target of approximately 13 m. The central portion of the flash begins to come out of saturation after approximately 600 ms.

A line graph of pixel intensity near the center of the flash (row 263, column 244) as a function of time is shown in figure 4. The intensity comes out of saturation at t = 640 ms which was 580 ms after the first appearance of the flash. The intensity decreases rapidly but does not approach its value before the flash until the very end of the sequence.

Figure 5 shows images of the gun just before firing and on the last frame of recorded imagery from this shot (2.28 s after firing). The gun is completely masked by the smoke and dust and there are many small hot particles that appear like burning embers evident in the image.

3.2 Shots at 260 m Range

As shown in the previous section, the effects of the muzzle flash are overwhelming at a range of 100 m. In addition, the computer that controlled the MWIR camera locked up (presumably due to the large amount of vibration) on each of the first two shots preventing the acquisition of MWIR imagery at that range. For these reasons, the rest of the imagery acquisitions were taken from an armored box that was 260 m from the gun and 20 m from the center of the shot line.

As shown in table 2, there were six shots fired with the cameras at the 260 m station but only two of the shots (numbers 4 and 5) yielded good imagery from both cameras. The data from these two shots were very similar; however, owing to a fortunate timing of the trigger pulse, the LWIR camera was able to capture the very beginning of the muzzle flash when the KE round was just leaving the end of the gun barrel.

Figure 2. Images of the muzzle flash from just before firing to 200 ms after firing as seen by the LWIR camera at a range of 100 m from the gun.

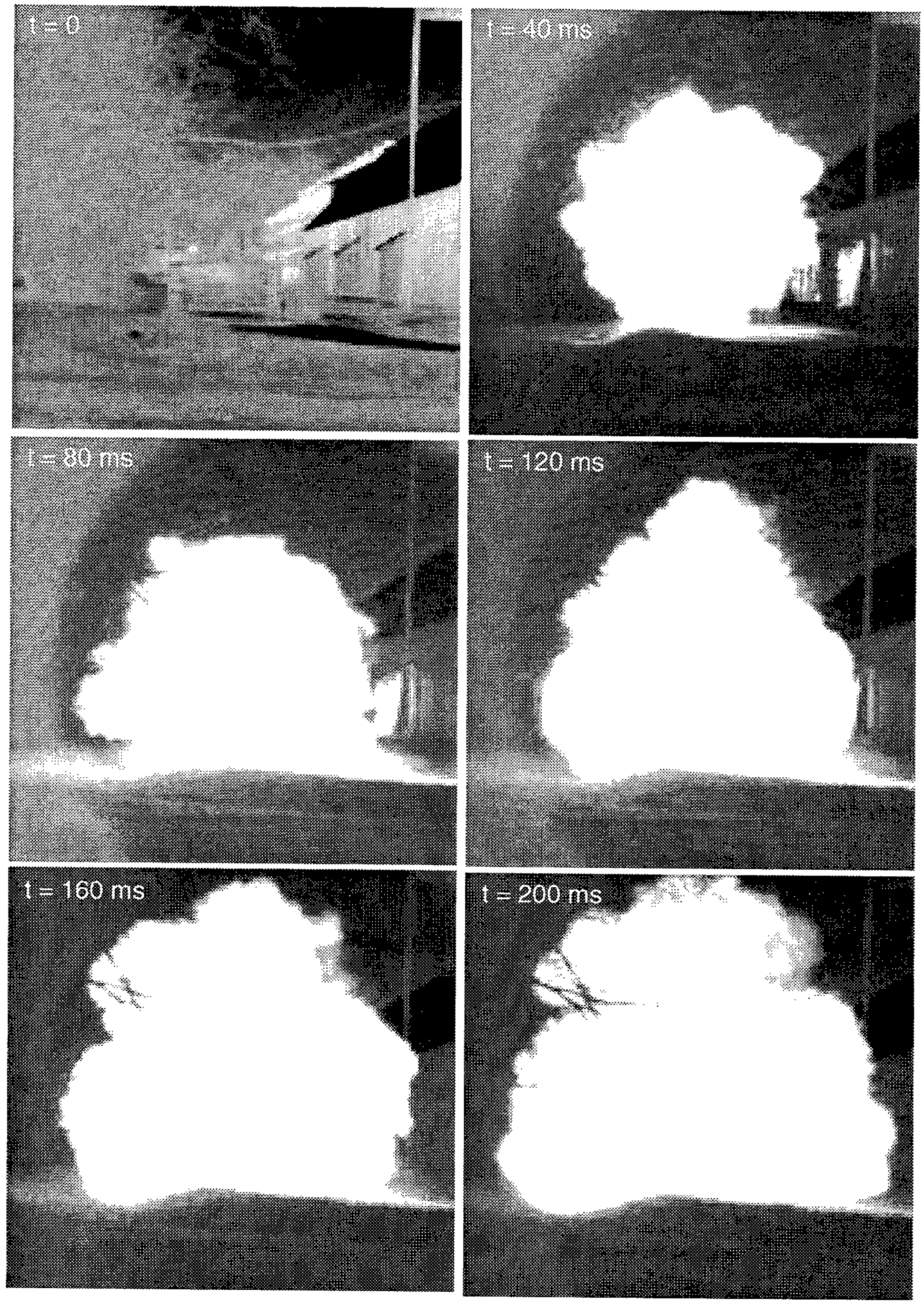
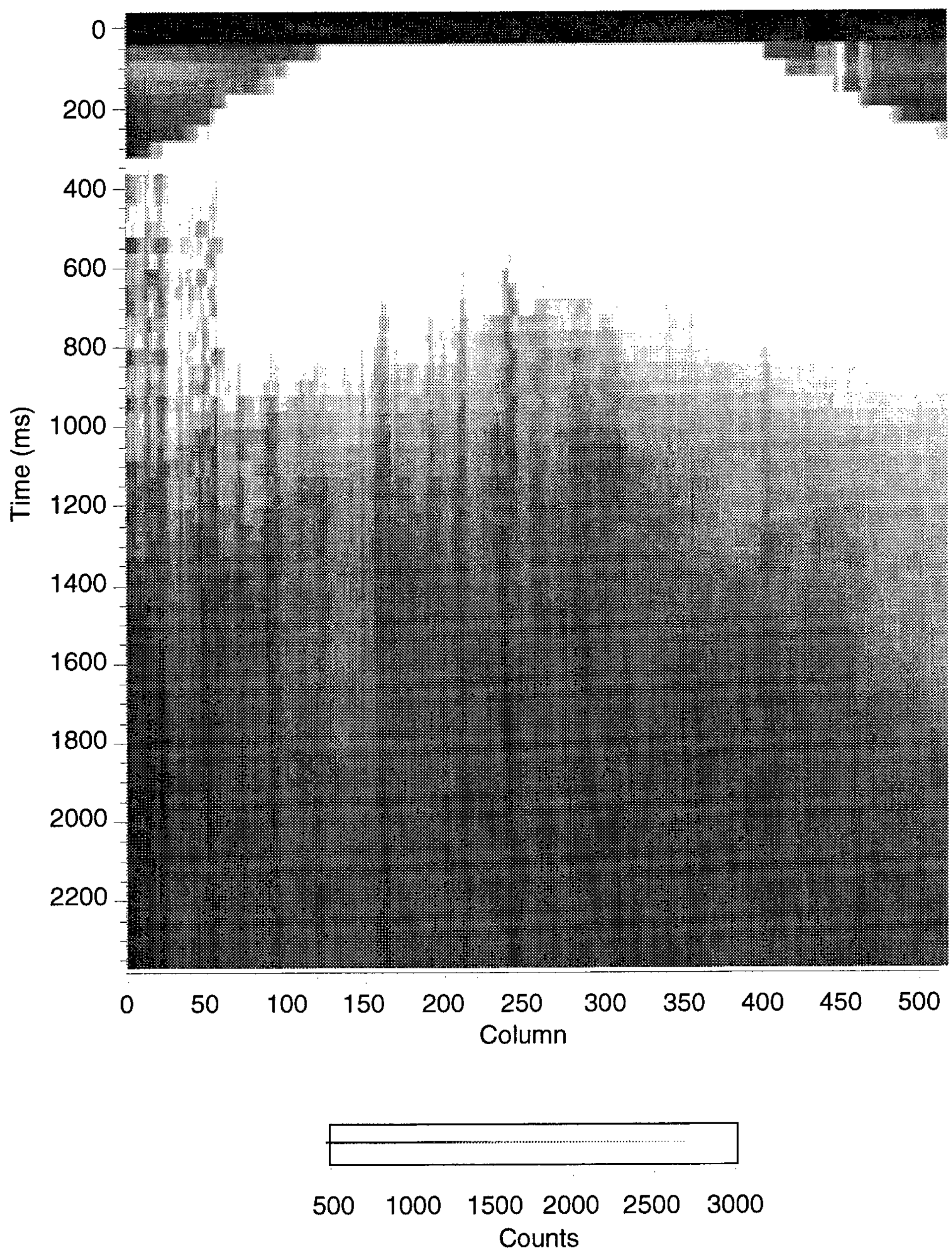
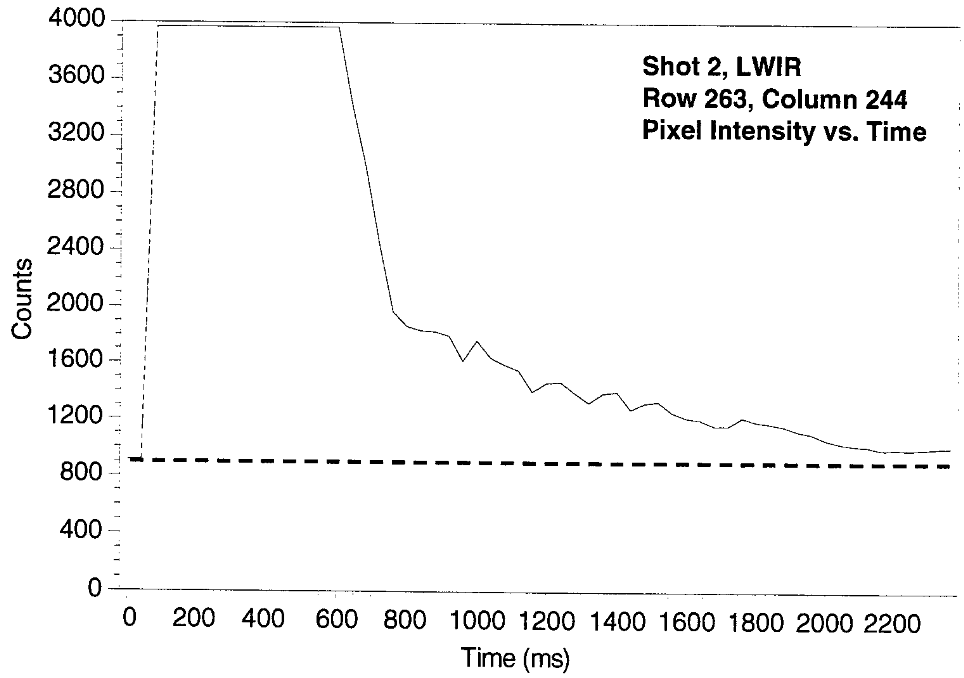


Figure 3. LWIR image intensity (counts) as a function of time and column number for a single row (number 236) of the sequence of images.



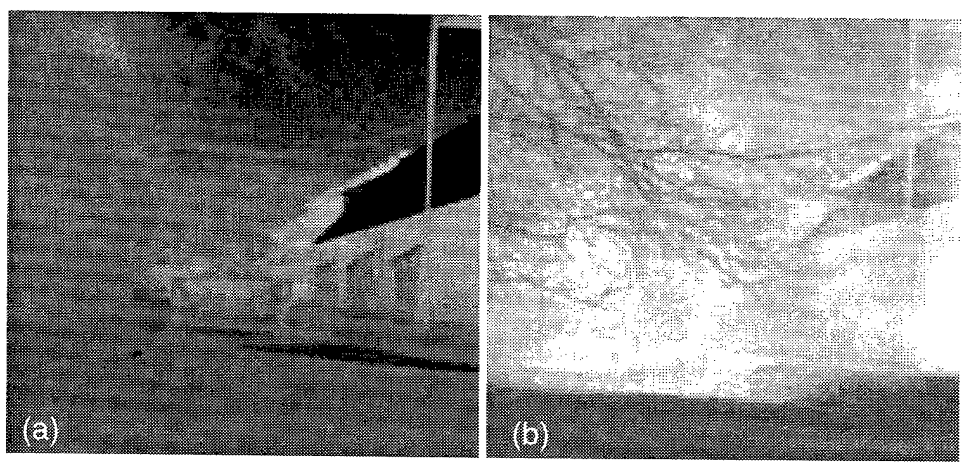
Note: The intensity begins to come out of saturation near the center of the image after approximately 650 ms from the initial flash.

Figure 4. Pixel intensity versus time for a pixel near the center of the flash (row 263, column 244).



Note: Each frame time was assumed to be 25 ms. The dashed line shows the baseline intensity before the shot.

Figure 5. LWIR images (a) just before firing and (b) 2.28 s after firing.



Notes:

1. The images are shown at equal values of brightness and contrast.
2. The gun is completely obscured by the smoke and dust generated by the gunfire and the large number of small hot particles created by the blast.

Images of the initial stages of the muzzle flash of shot 5 taken with the LWIR camera are shown in figure 6. In figure 6(c) and 6(d) it is possible to observe the KE round and the three sabots as well as the muzzle flash. In figure 6(d) the saturated portion of the flash covers between 105 and 110 pixels, which implies that the extent of the muzzle flash is between 6.5 and 6.8 m.

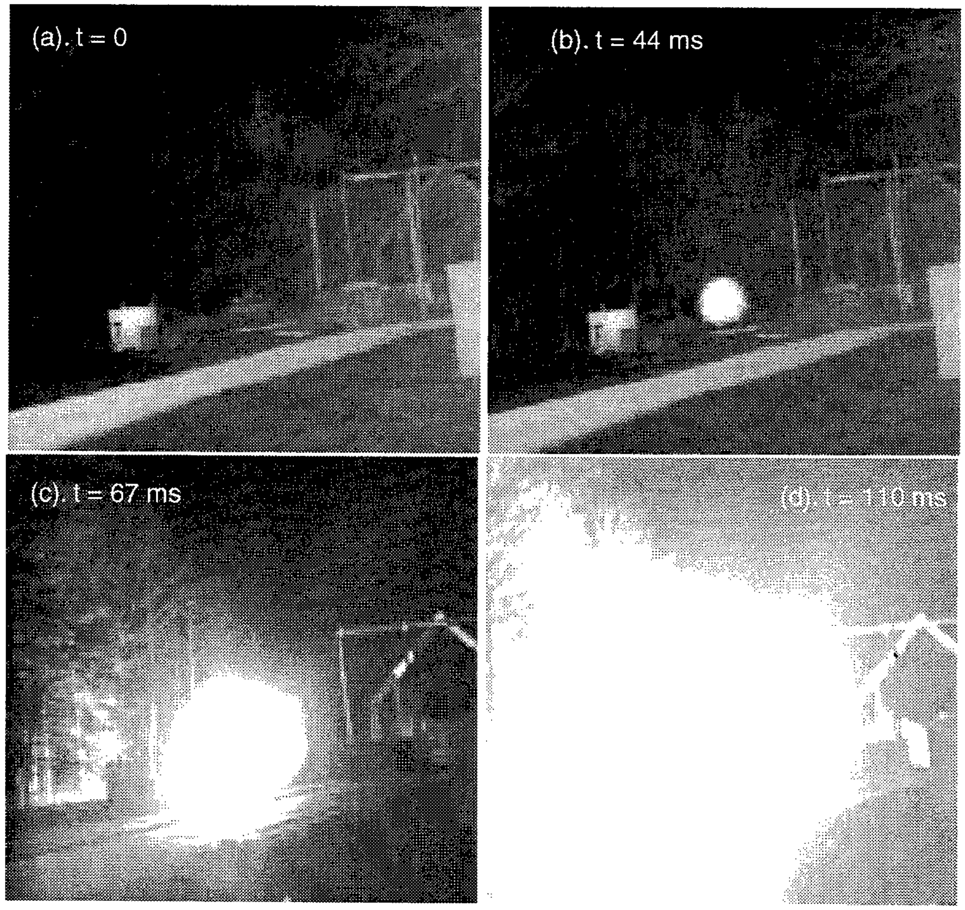
Figure 6. LWIR images of the initial stages of the muzzle flash on shot 5.

Note: In images (c) and (d) it is possible to observe the KE round and the 3 sabots.

Images of the initial stages of the muzzle flash of shot 5 acquired with the MWIR camera are shown in figure 7. The nature of this imagery is quite different from the LWIR camera. In figure 7(b), which was acquired at 44 ms after the trigger, the flash covers a small area approximately 40 pixels wide surrounding the gun. However, in the next frame figure 7(c) the flash has grown greatly in extent and intensity. A large amount of reflected intensity is evident from the trees on the left side of the image. In figure 7(d) the flash dominates the entire image. Unlike in the LWIR sequence shown in figure 6, it is impossible to locate the KE round or the sabots in the MWIR images with any certainty. Similar results were seen in the imagery from shot 4.

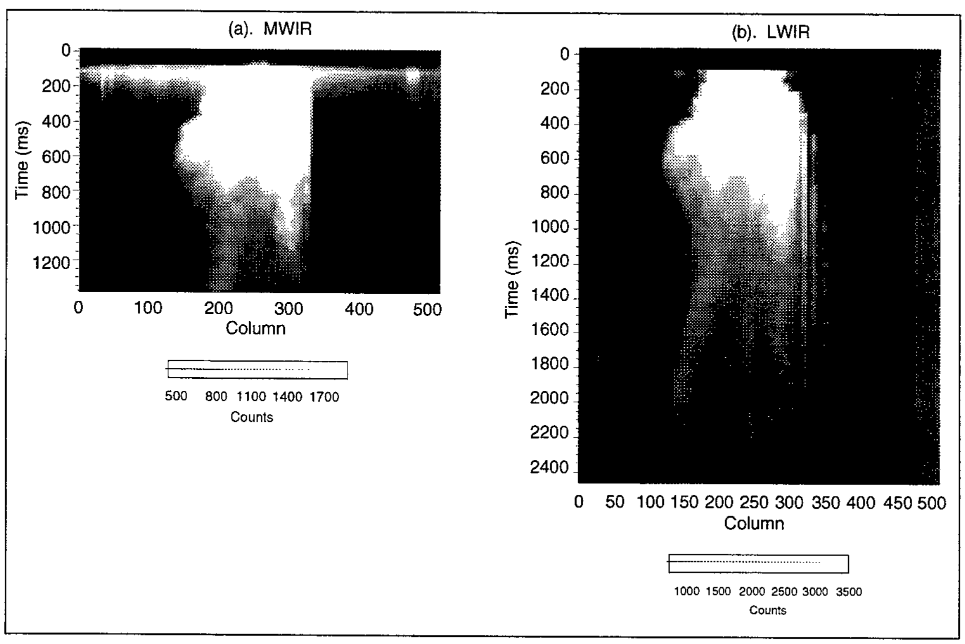
Figure 8 shows the pixel intensities for the MWIR camera (a) and the LWIR camera (b) as functions of column number and time for single rows of the FPAs (the row closest to the center of the gun). For the MWIR data, row 317 was used and for the LWIR data, row 306 was used. The two images are shown with equal scales of the time axes reflecting the shorter time period covered by the MWIR data (compared with that for the LWIR camera). The figure shows that in the first few frames after the gun fired, the MWIR camera was saturated over nearly the entire image. By comparison, the only regions of the LWIR imagery that were saturated were those taken up by

Figure 7. MWIR images of the initial stages of the muzzle flash on shot 5.



Notes: Neither the KE round nor the sabots can be seen with any certainty.

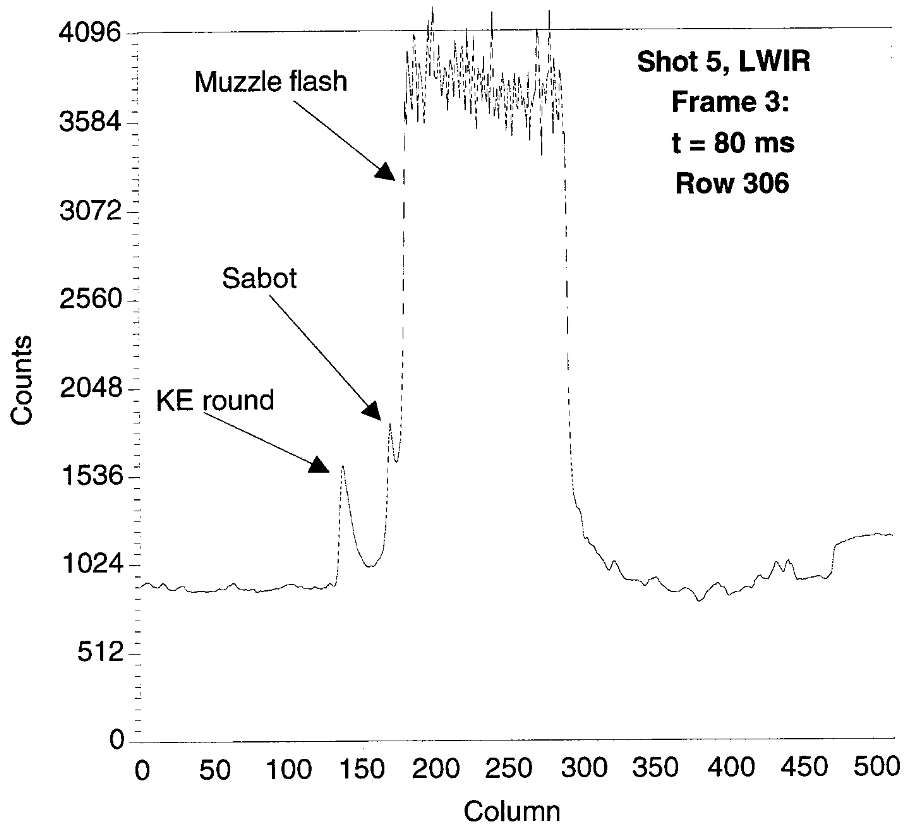
Figure 8. Images of the pixel intensity as functions of column number and time for (a) MWIR row 317 and (b) LWIR row 306 for shot 5.



the muzzle flash itself. The maximum extent of the flash in the LWIR image was about 185 pixels, which occurred 520 ms after the trigger pulse (440 ms after the first appearance of the flash). This corresponds to a diameter width of 11.5 m at the target. In the MWIR imagery, once the initial saturation of the entire image died away, the extent of the flash grew to a maximum of 180 pixels in width, very nearly the same as that seen in the LWIR.

In figure 9, the intensity observed at the pixels in row number 306 of the FPA is plotted as a function of column number for a single frame of the imagery from shot 5. In this frame, shown in figure 6(c), the KE round and

Figure 9. Pixel intensity versus column number for row 306 of frame 3 of the image data from shot 5.



Note: The peaks to the left of the muzzle flash have been identified as the signatures of the KE round and one of the sabots, respectively.

Table 3. Pixel intensities for the KE rounds and the sabots in the LWIR imagery.

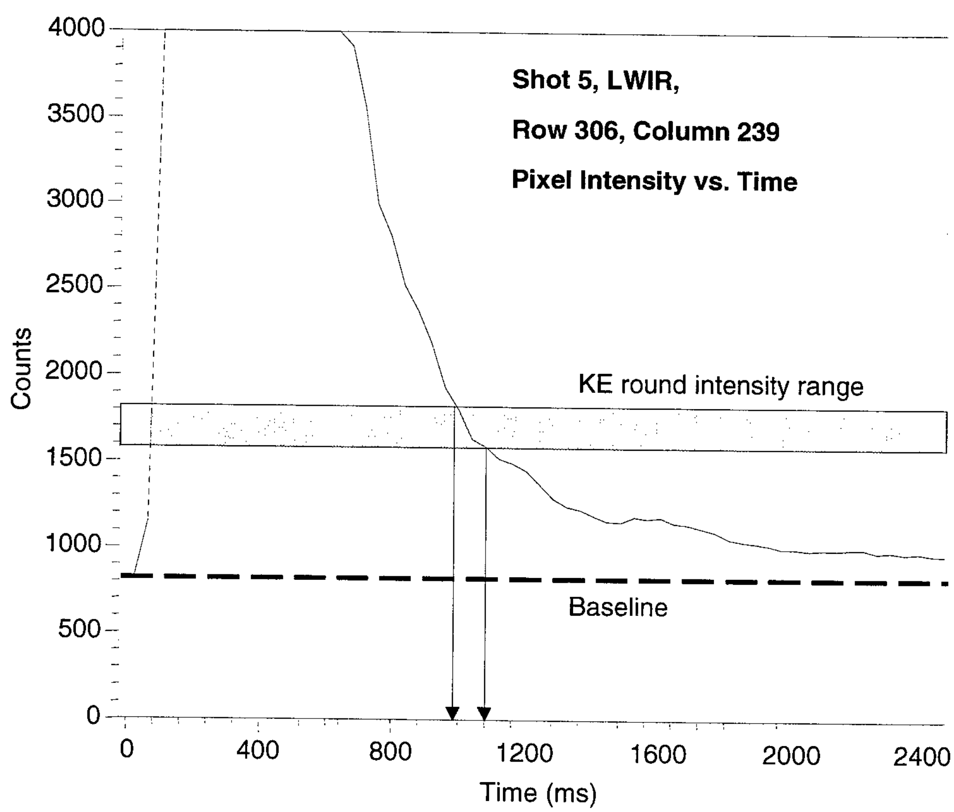
Shot	KE round	Sabots frame 3	Sabots frame 4	Sabots frame 5
3	1803	2132, 1442	1550, 1120, 1398	—
4	1682	1412, 1365	1491, 1232	1153
5	1600	2437, 1949, 1853	1520, 1341, 1136	1662, 1288
8	1823	1889, 1666, 1737*	1250, 895*	—

*For shot 8, frames 2 and 3 were used.

all three sabots are visible to the left of the muzzle flash in the LWIR imagery. The maximum intensity of the KE round was 1600 counts. The KE round was also identified in the LWIR imagery from other shots observed at the 260 m range. The maximum pixel intensities of the rounds and the sabots measured for each of the shots are shown in table 3. In many cases, the intensities of the sabots were greater than those of the KE rounds.

The time evolution of the central part of the muzzle flash of shot 5 (in the LWIR) is shown in figure 10. The data show the intensity at a particular pixel as a function of time. The LWIR time profiles for shots 3 and 4 are shown in figures 11 and 12, respectively. The intensity of the muzzle flash does not fall to the levels observed for the rounds until approximately 1 s after firing. In that time, the round would have traveled 1.6 km from the gun. It was not possible to identify the KE round in either of the MWIR image sequences; therefore, I was not able to compare the round's MWIR signature with that of the muzzle flash.

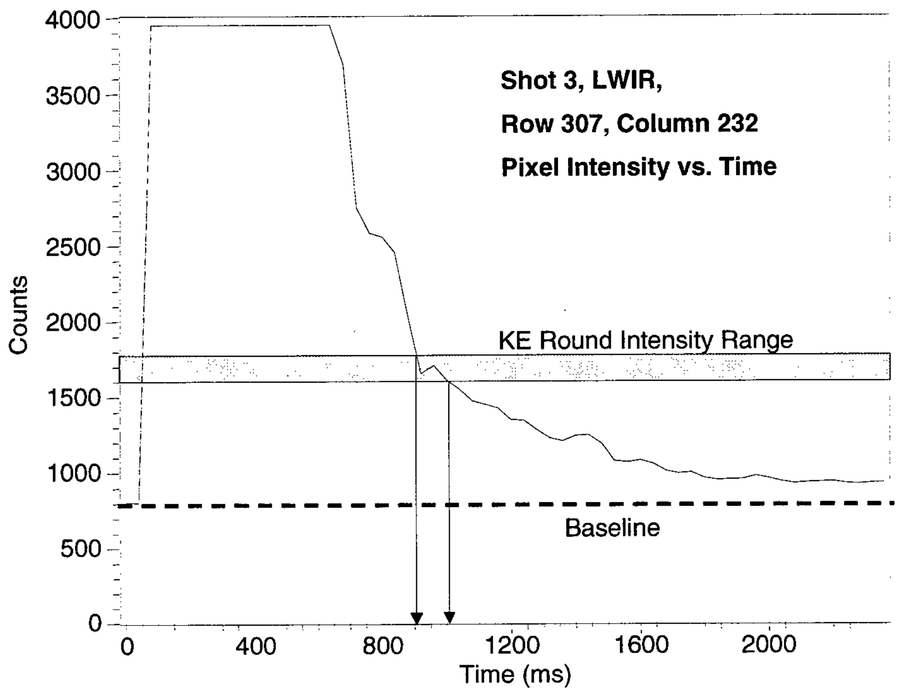
Figure 10. Pixel intensity versus time for pixel at row 306, column 239 in the LWIR imagery from shot 5.



Note:

1. This pixel was the closest to the center of the gun barrel.
2. The grey area shows the range of intensity of the KE rounds observed in all shots, and the dashed line is the baseline intensity before the shot.

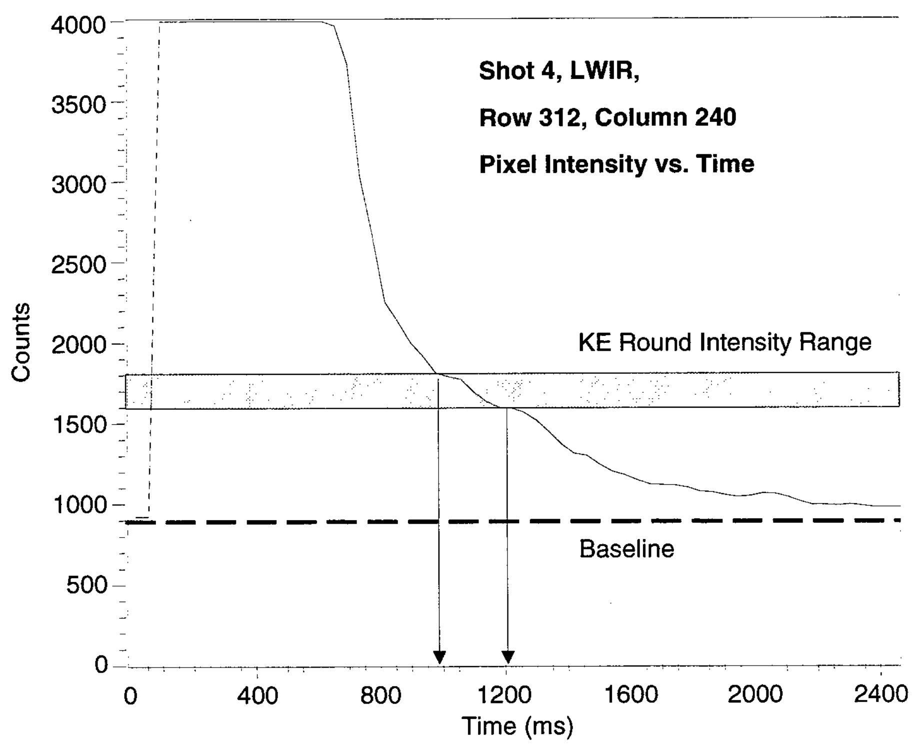
Figure 11. Pixel intensity versus time for pixel at row 307, column 232 in the LWIR imagery from shot 3.



Notes:

1. This pixel was the closest to the center of the gun barrel.
2. The grey area shows the range of intensity of the KE rounds observed in all shots and the dashed line is the baseline intensity before the shot.

Figure 12. Pixel intensity versus time for pixel at row 312, column 240 in the LWIR imagery from shot 4.



Notes:

1. This pixel was the closest to the center of the gun barrel.
2. The grey area shows the range of intensity of the KE rounds observed in all shots and the dashed line is the baseline intensity before the shot.

Figure 13 shows LWIR and MWIR images from shot 5 taken 1.35 s after the trigger pulse (corresponding to 1.30 s after firing of the gun). In the MWIR image, the contrast between the hotter parts of the remnants of the flash is significantly greater than that in the LWIR image. In addition, there are many small hot particles flying around in the smoke cloud in the MWIR image; these are not apparent in the LWIR image.

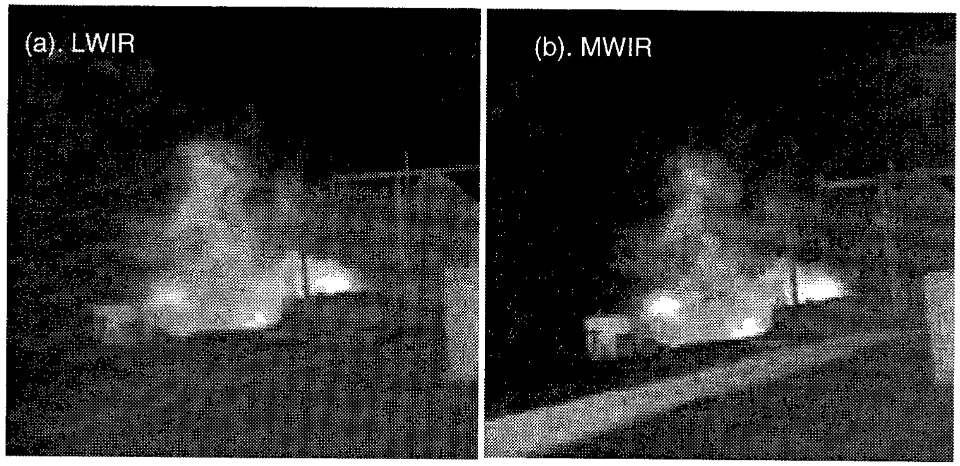


Figure 13. LWIR (a) and MWIR (b) images of the muzzle flash of shot 5 taken 1.35 s after the trigger (1.30 s after firing).

4. Summary and Conclusions

This research measured the extent in time and space of the IR signature of the muzzle flash of a 120-mm tank gun as viewed from head-on in both the MWIR and LWIR bands using state-of-the-art focal plane arrays. The results of these tests were consistent over the several shots observed. This research also captured the LWIR signatures of the M865 KE round and the sabots that surround it in the gun and are jettisoned just after firing. The muzzle flash caused the MWIR camera to saturate over nearly the entire image for several frames. This made it practically impossible to isolate the round or the sabots from the background. Even if the overwhelming blooming was not present, the large amount of reflected light evident in the MWIR imagery would have made picking the round or the sabots out of the background a very difficult task. The cause of the blooming in the MWIR imagery is not known with certainty. The effect could be due to instabilities of the photodiodes in the array caused by the injection of a large amount of charge (due to the high photon flux of the flash). It could also be due to insufficient isolation of the charge wells in the read-out circuit. It should also be noted that the InSb photodiode array used in the MWIR camera is similar in design to HgCdTe photodiode arrays used in LWIR imagers. The detectors in the LWIR array used in this test were GaAs/AlGaAs QWIPs (quantum wel infrared photodetector). Cameras using these arrays have been shown to be particularly immune to blooming at large signal levels.[1] It may be the case that any conventional photodiode array subjected to the large transients seen in this test will be susceptible to blooming.

The LWIR imagery showed no blooming and no part of any of the images outside of the muzzle flashes were saturated. Even with an integration time of less than 0.5 ms, the image of the muzzle flash was saturated for more than 500 ms. The maximum width of the muzzle flash was calculated to be approximately 11 m at the position of the gun. The maximum extent of the flash occurred between 500 and 600 ms after the gun was fired. From the time profile of the flash and the observed signature of the round, I calculated that the round would become visible above the background of the flash approximately 1 s after the gun was fired. Therefore, to acquire a round that was fired with little elevation (as it would if the shooter was relatively close by), it could be as much as 1 s before tracking could be started by using its IR signature. In that time, the round would have traveled at least 1.5 km downrange from the shooter. If, however, the round is fired with enough elevation to bring it over the top of the muzzle flash, it could be acquired and tracked for a considerably longer period of its trajectory. The

[1] There are no published data confirming this conclusion; it is based on the author's observations of field tests done with a QWIP LWIR camera viewing hot rocket plumes and the sun.

maximum extent of the top of the muzzle flash is approximately 5.5 m from the gun. At a range of 1 km, this corresponds to a viewing angle of 0.31°.

The results of this test suggest that the performance of the LWIR imager was superior to the MWIR in acquiring the KE target in the presence of the large muzzle flash. However, I found that in the first moments after the round emerges from the gun, the sabots have a comparable or higher LWIR signature to that of the round. The signatures of the sabots die away rather quickly while that of the round would be expected to stay the same or increase. It is apparent that more data need to be taken, particularly at ranges farther from the gun, which will better simulate the real-world conditions that a KEAPS will face.

Acknowledgements

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Acronyms

ARL	Army Research Laboratory
DU	depleted uranium
FPA	focal plane array
IFOV	instantaneous field of view
IR	infrared
KE	kinetic energy
KEAPS	Kinetic Energy Active Protection System
LWIR	long-wavelength infrared
MWIR	medium-wavelength infrared
QWIP	quantum well infrared photodetector
SEDD	Sensors and Electron Devices Directorate
UV	ultraviolet
WMRD	Weapons and Materials Research Directorate

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13. ABSTRACT *(Maximum 200 words)*
This report examines the results of infrared (IR) imaging of the firing of M865 kinetic energy (KE) rounds from a 120-mm tank gun in support of the Kinetic Energy Active Protection System (KEAPS) development. The primary objective was to determine the extent in time, space, and intensity of the muzzle flash in both the 3 to 5 μm (medium-wavelength IR or MWIR) and 8 to 12 μm (long-wavelength IR or LWIR) wavelength bands. The secondary objective was to determine whether or not the IR cameras could detect the KE rounds and/or their sabots and to what extent the sabots could cause false targets for a prospective active protection system. Results showed that the brightest parts of the muzzle flash extended up to 10 m on either side of the gun and that the intensity of the flash was enough to saturate the imagery for more than 0.5 s in each wavelength band. Additionally, the MWIR camera was essentially blinded for several frames soon after the gun was fired while the LWIR camera was able to provide high fidelity imagery for the entire duration of the flash. In addition, the LWIR camera was able to detect the KE round and the sabots consistently.

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