NIST Technical Note 1491

Performance of Thermal Imaging Cameras In High Temperature Environments

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National Institute of Standards and Technology • U.S. Department of Commerce

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Table of Contents

ABSTRACT

Thermal imaging cameras used by firefighters and other emergency responders must maintain acceptable image quality while operating in the severe conditions of a fire environment. Currently, there are no standard performance metrics for these cameras. This work investigates the impact of elevated temperatures on the operation of three different thermal imaging cameras. A heated air flow loop was used to provide the elevated thermal environment, and a variable temperature target served as a viewing object. Results of the testing are presented.

INTRODUCTION

Firefighters working a building fire face a combination of severe environmental conditions, which include elevated temperatures, high humidity, thermal radiation, and smoke. Thermal Imaging Cameras (TICs) are often used by firefighters to identify hot spots or to do search and rescue operations. TICs are challenged to operate under the harsh conditions of the fire environment, which can impede the normal operation of electronic equipment. Performance standards need to be developed for TICs that are consistent with the fire environment experienced by firefighters.

Currently, it is up to the manufacturers of TICs to set performance metrics and to test their equipment to ensure it meets these metrics. As of this writing, there are no universal performance metrics or standardized test methods for TICs. The National Fire Protection Association (NFPA) is in the process of developing performance standards; however, they are still in the planning stages. Researchers at the National Institute of Standards and Technology (NIST) are currently developing performance evaluation techniques to characterize TIC image output in ambient operating conditions (Amon *et al.*, 2006; Amon and Hamins, 2006; Amon *et al.*, 2004).

The effect of elevated temperatures on the operation of TICs was examined as part of an ongoing effort by NIST to characterize the effects of building fire environments on electronic equipment. During previous work, (Donnelly *et al.*, 2006) the expected conditions encountered by firefighters and the various classifications of these conditions were investigated. Through research and experimental testing, thermal classes for electronic equipment exposures were developed by NIST. These thermal classes were used as guidelines for testing TICs at elevated temperatures. Table 1 shows the sustained air temperature and corresponding exposure time used to test the equipment for these thermal classes. Operation at the preceding thermal class was required before testing at a higher class.

The thermal response of a small sample of TICs was evaluated to determine the feasibility of developing thermal standards for the TICs. The goal was to investigate operational response to elevated temperatures, test TIC image targets, and evaluate the testing equipment, in order to provide recommendations for TIC thermal standards. The purpose of these tests was *not* to rank the performance of cameras by different manufacturers. Only one sample of each type of camera was used for testing.

Table 1 Thermal Classes for Testing Electronic Equipment

Thermal Class	Exposure Time (min)	Sustained Air Temperature (°C)/(°F)	Additional Temperature Requirements
I	25	100/212	none
II	15	160/320	Thermal Class I
III	5	260/500	Thermal Classes I and II

Equipment and Testing Procedures

The Fire Equipment Evaluator (FEE) provided the thermal environment for testing the TICs. The FEE is a heated, recirculating air flow loop, driven by a high temperature blower, which produces a controlled and repeatable thermal environment for testing. A diagram of the FEE is shown in Figure 1. The air flows through the stainless steel loop at velocities from 0.5 m/s to 2.0 m/s, with temperatures up to 300 ºC. The FEE measures 220 cm long by 174 cm high and contains a testing section that is 91 cm long, with a cross section area of 38 cm by 38 cm. Thermocouples throughout the loop provide temperature measurements at various locations. A bidirectional probe is used for the velocity measurements. Further details concerning the components and operation of the FEE can be found in Donnelly *et al.*, 2006.

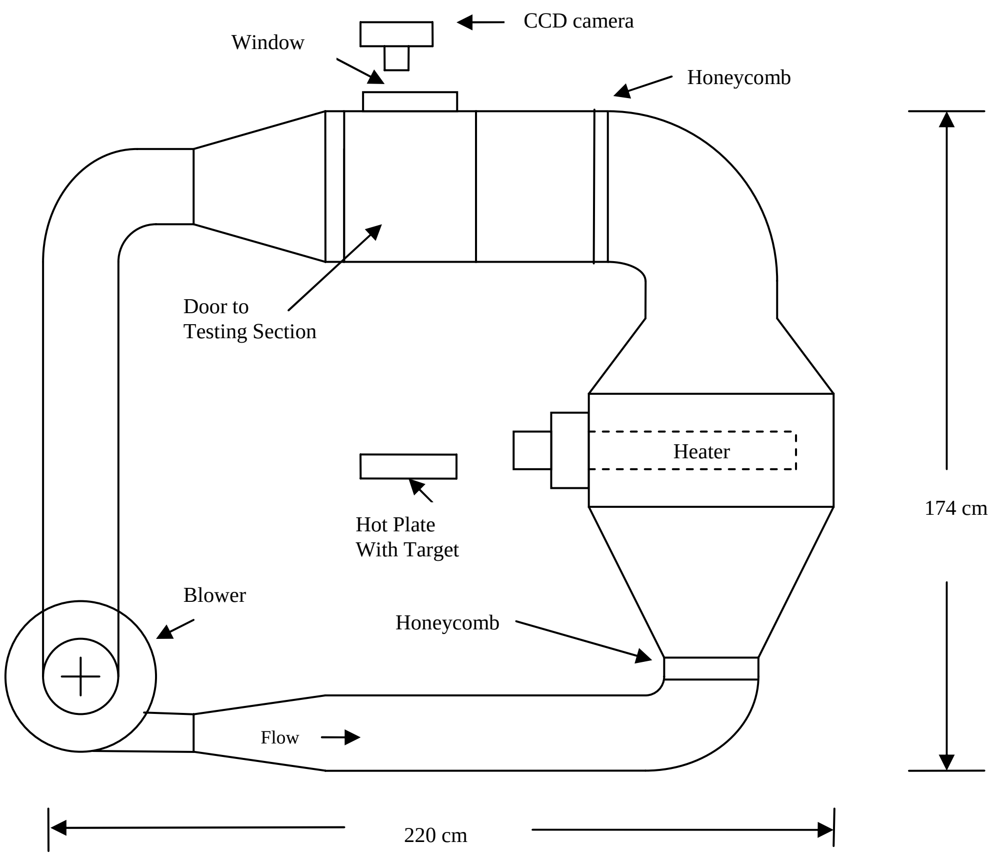

Figure 1 Diagram of Fire Equipment Evaluator (FEE)

During testing, each TIC was placed in the testing section of the FEE, which was accessed through a door on the side of the FEE as indicated in Figure 1. The TIC was positioned so that its display screen faced upwards toward a window on top of the FEE. To monitor and collect images of the TIC display screen, a CCD camera was placed outside the FEE, above the window and was aligned to view the TIC display screen. The CCD camera output signal was relayed to a PC where it could be continuously monitored, and still images could be saved.

To evaluate the TIC displays, a variable temperature target was constructed. The target was made using 2.54 cm diameter Bakelite rods spaced 2.54 cm apart in a fixed vertical pattern. The rods were supported 0.3 cm above a hot plate with an area measuring 23 cm by 23 cm. The Bakelite rods and the surface of the hotplate were both painted with an optical black coating with an average emissivity of 0.94. The hot plate had an adjustable temperature range from ambient to 100 °C. When the plate was heated, the result was a temperature bar target with alternating areas of lower and higher temperatures when viewed from above, formed by the pattern of the Bakelite rods above the hot plate. Thermocouples measured the surface temperatures of the rods and the hotplate. For all of the elevated temperature tests, the hotplate was set to a temperature of 30 °C ± 3 °C. This tested the TICs in the high sensitivity mode, distinguishing a temperature difference of approximately 10 °C between the temperature of the hot plate and the temperature of the bakelite rods. Figure 2 is an infrared picture of the target, as viewed by a TIC. The light areas indicate the higher temperatures.

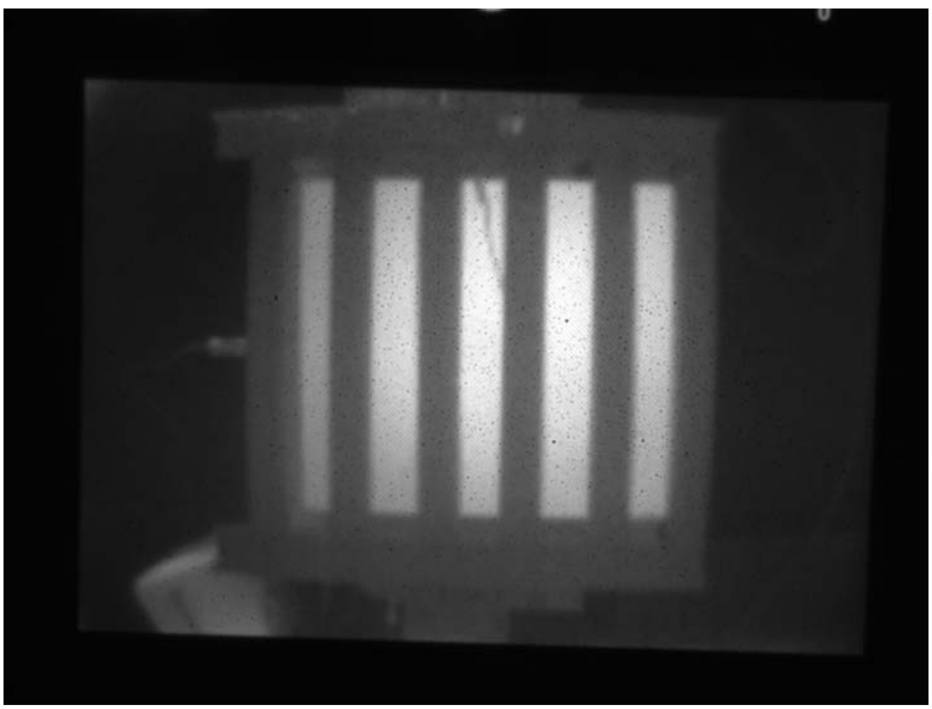

Figure 2 Photograph of TIC target as viewed by a TIC.

The TIC temperature target was placed below the testing section of the FEE, at a distance of 56.5 cm from the TIC lens. A 5 cm diameter hole was cut into the bottom of the FEE testing section, and was left open and uncovered, so that the TIC had an unobstructed line of site to the target. Flow evaluation tests verified that the viewing hole had a negligible effect on the TIC temperatures and flow patterns in the testing section. Figure 3 shows a photograph of the FEE setup, with the CCD camera above the testing section and the temperature target located below. The door to the FEE testing section is open in the photograph.

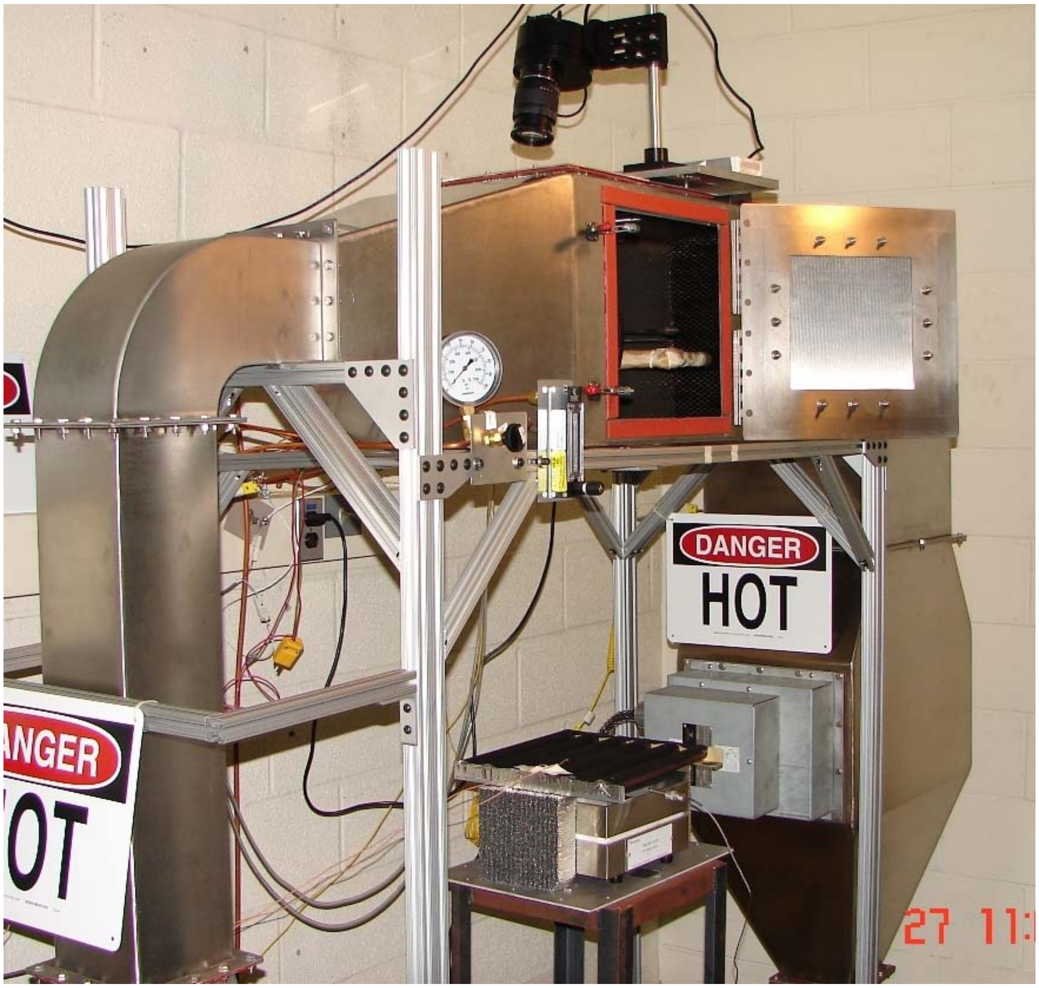

Figure 3 Photograph of the FEE, set up for TIC testing.

For thermal evaluation tests, a TIC was placed in the center of the testing section while the FEE was at ambient temperature. Ambient temperatures for these tests ranged from 20 °C to 24 °C. The TIC was positioned above the viewing hole, with an image of the target centered on its screen. Then the CCD camera was aligned and focused on the TIC image screen. At the beginning of each test, while the TIC and the test tunnel were at ambient temperature, initial TIC screen images were saved as baseline images. Next, the heater was activated, and the TIC was subjected to a heat-up time, which varied for each thermal class, but was repeatable for all tests conducted at the same temperature. The heat-up time was 330 s for the 100 °C, Class I tests, 400 s for the 160 °C, Class II tests, and 700 s for the Class III, 260 °C test. Once the airflow inside the FEE reached the desired temperature, it was maintained at this temperature for the corresponding exposure time specified in Table 1.

The TIC image display was also monitored during the cool down period following each elevated temperature test. Cameras were allowed to cool completely, reaching ambient room temperature between tests. Batteries were fully charged between tests, and the TICs were placed inside the FEE with a full battery charge at the start of each thermal test. Some battery usage occurred during the camera alignment prior to heating, which typically took approximately 10 minutes.

RESULTS

Three TICs, each from a different manufacturer, were exposed to elevated temperatures, using the thermal classes listed in Table 1 as the guidelines for camera exposures. For all tests, the blower motor speed was set at a rotation of 20 Hz. This resulted in an air flow velocity through the testing section of 0.83 m/s ± 0.05 m/s for the Class I and Class II temperatures, and 0.93 m/s ± 0.05 m/s at the Class III temperature, and is comparable to a slow walking speed. A plot of the measured velocity at the three different temperatures is shown in Figure 4. The viewing screen of each camera was continuously monitored throughout the test, and stills from the CCD camera were periodically saved. In addition, objects were moved in and out of the TIC field of view, above the target, to ensure that the camera was working and that the screen did not become frozen on an image.

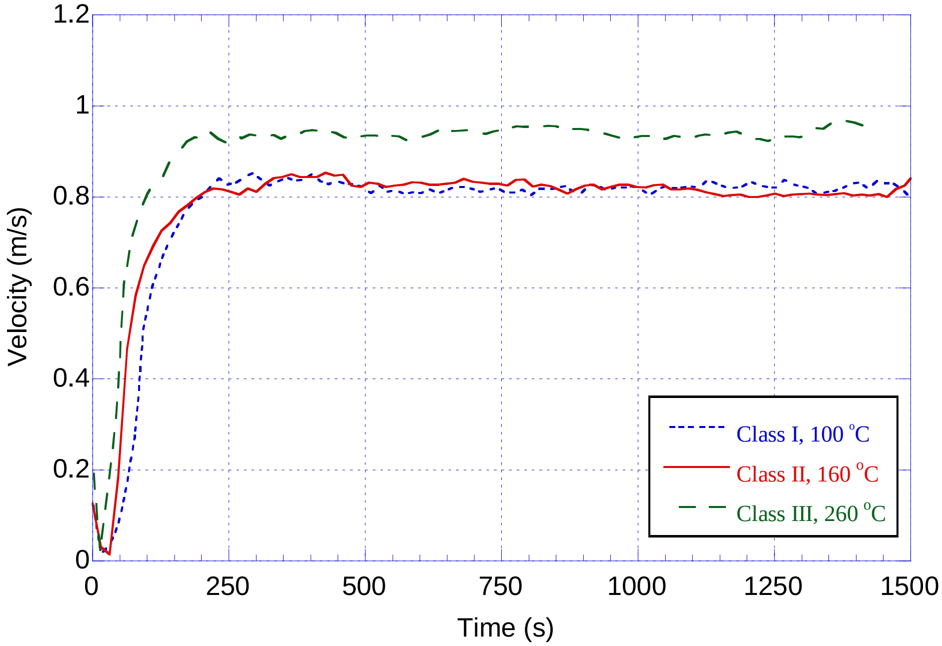

Figure 4 Velocity measured in the FEE test section at three different temperatures.

The temperatures inside the tunnel were measured at different locations during the testing. Thermocouples placed in a row vertically measured the temperature at various heights at the center of the testing section, approximately 3 cm upstream of the camera. Two thermocouples were also attached to each TIC. One thermocouple measured the temperature of the image viewing screen, which faced the top of the tunnel. A second thermocouple was attached to the body of the camera, on the side facing the FEE door, to monitor the outer temperature of the camera body. Figure 5, Figure 6, and Figure 7 show temperature measurements inside the FEE for Thermal Class I, Thermal Class II, and Thermal Class III conditions, respectively. Time zero indicates when the heaters are turned on, and the start time and end time for the timed temperature exposures is indicated. Figure 5 shows that the temperatures of the TIC body and the screen remained more than 10 °C cooler than the air temperature inside the FEE during the 100 °C tests. Temperatures of the TIC body and the screen were more than 30 °C cooler than the air during the 160 °C tests, as shown in Figure 6. For the Class III, 260 °C test, the FEE air temperature was approximately 90 °C warmer than the TIC screen temperature, as shown in Figure 7. During the Class III test, the thermocouple located on the TIC body stopped working approximately 400 s into the test, so no temperature was recorded at that location beyond 400 s.

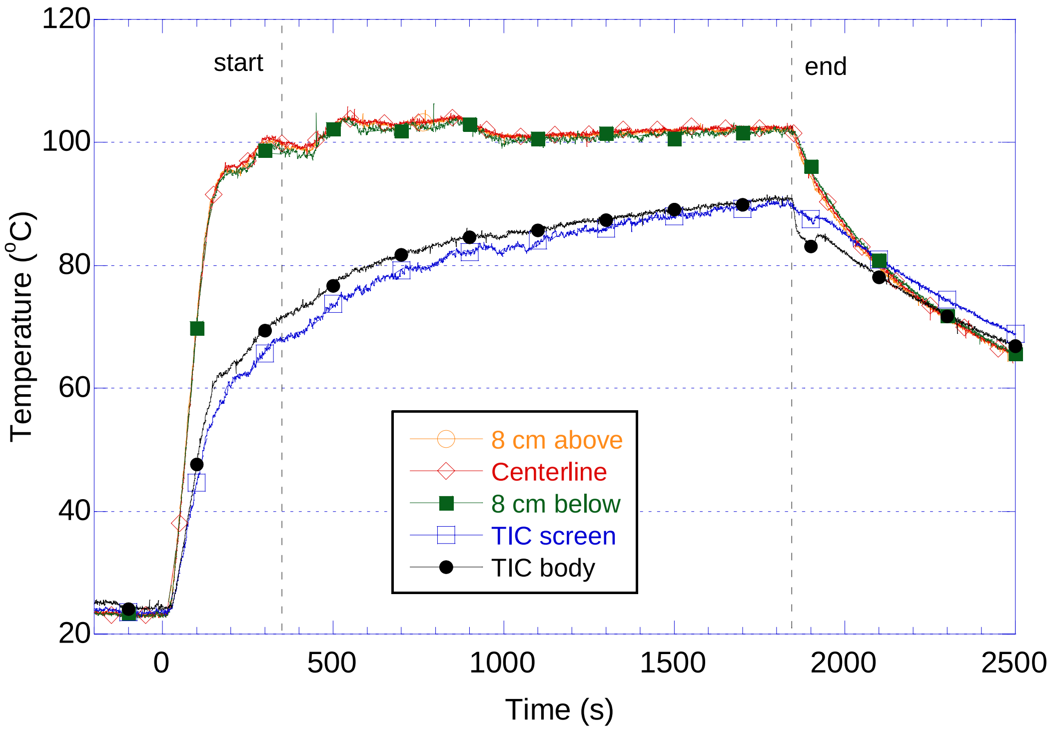

Figure 5 Temperature measurements at Thermal Class I, 100 °C.

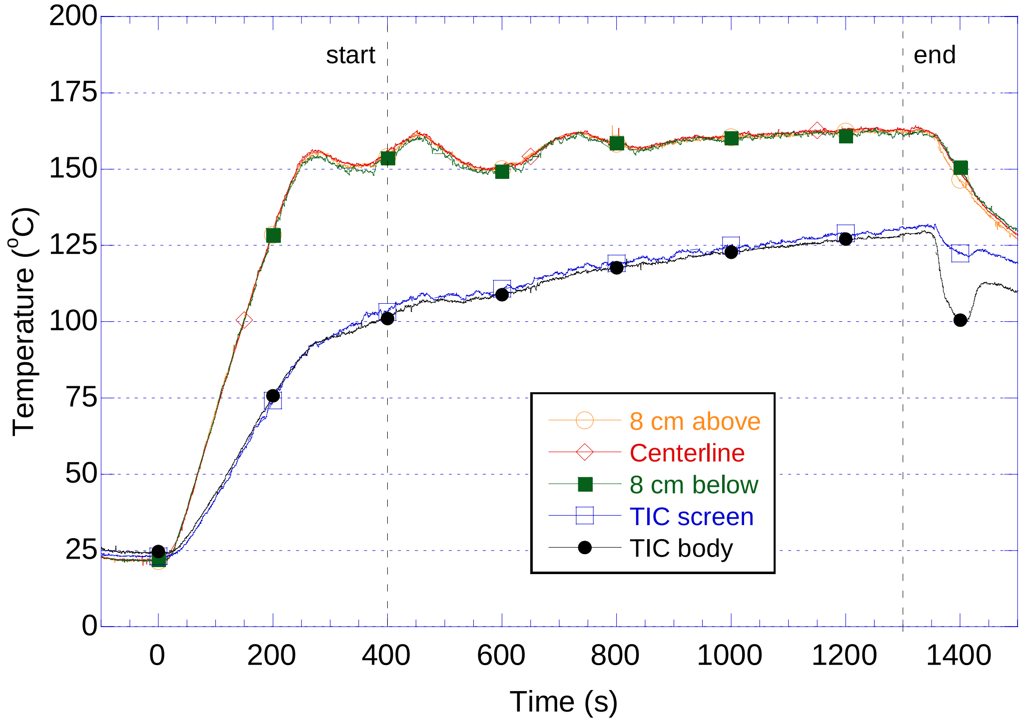

Figure 6 Temperature measurements at Thermal Class II, 160 °C.

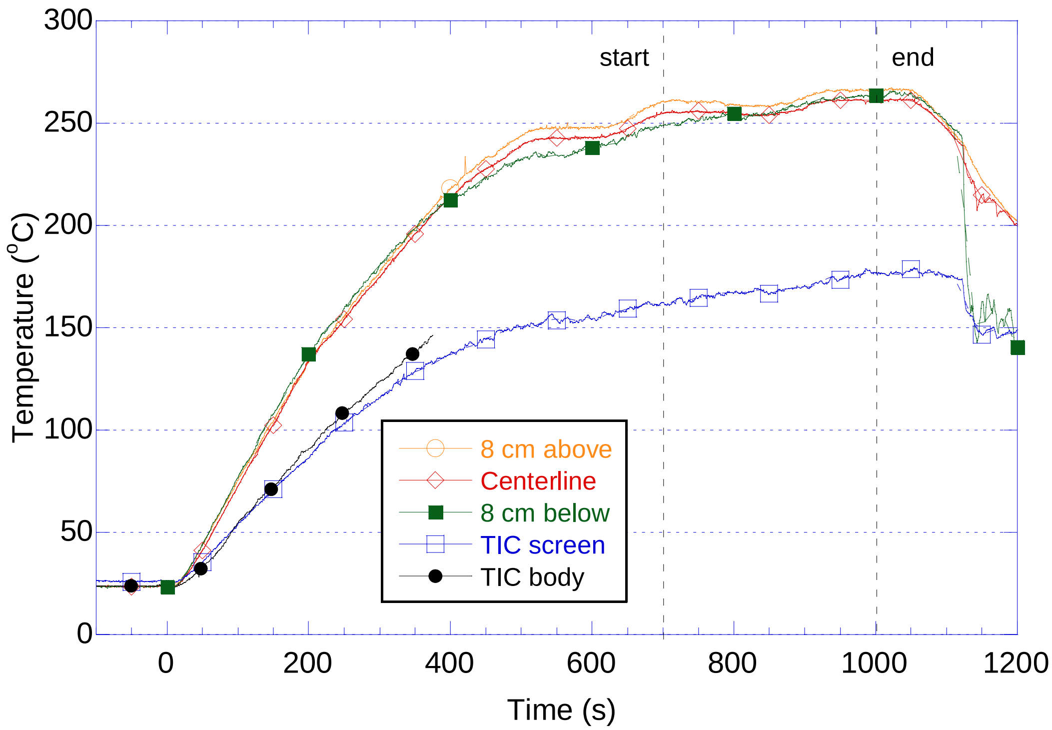

Figure 7 Temperature measurements at Thermal Class III, 260 °C.

Thermal Class I – 100 °C for 25 min

Camera 1 worked properly under the Class I conditions of exposure to an air temperature of 100 °C for 25 min, following the 330 s heat up period. There were no problems with the operation or visible degradation of the screen image. The camera continued to work throughout the heat soak and cool down. Inspection of the camera after the test showed no melting, warping, or damage of any kind to the camera or battery.

Camera 2 worked throughout the Class I conditions of 25 min at 100 °C without visible changes to the image on the display. The camera display remained unchanged during cool down and continued to function after the test. The camera was inspected after cool down, and showed no signs of damage to any parts of the camera or battery. There was one anomaly during this test. The battery indicator dropped quickly, moved back up to nearly full, then dropped quickly again, and repeated this throughout the heating. The up and down inconsistency of the battery indicator had no apparent impact on the camera operation, and the image was not affected. To determine if the abnormal response of the battery indicator was a result of the camera being heated, or a defect in the camera itself, the camera was allowed to cool overnight, and was then operated at ambient temperature for one hour. During this time the battery indicator was observed, and no anomalies were witnessed while operating the camera at ambient temperature.

Camera 3 worked properly throughout the Class I conditions of 100 °C temperatures for 25 min. There were no degradations of the picture during the test. A “high temperature” warning appeared on the camera screen near the end of the thermal exposure, at 22.75 min, but there was no observable change in the camera image as a result of the warning. Inspection of the camera after the test showed no melting, warping or any other observable damage to any parts of the camera. The camera was fully functional after the Class I test.

Thermal Class II – 160 °C for 15 min

Camera 1 functioned properly throughout the Thermal Class II conditions of exposure to 160 °C for 15 min, following the standard 400 s heat up period. The camera image remained clear, and there were no signs of image degrading during the heat exposure or cool down. After the test, the camera was inspected. There was no observable damage to the camera or battery. Camera operation was normal following this test.

Camera 2 only worked for the first few minutes at the Class II temperature of 160 °C. At a time of 168 s into the thermal exposure, the image suddenly disappeared, and the screen was filled with static. The occurrence was abrupt, and there was no blurring or distorting of the image and no warning from the camera; the screen simply went from showing a clear image to showing only static. The battery indicator was still functioning and indicating a mostly full battery. Other than the picture no longer working, there was no noticeable damage to any other parts of the camera. Camera 2 was allowed to cool overnight, and the battery was replaced; however, operation of the camera was not restored.

Camera 3 functioned normally during the 15 min exposure at the Class II temperature of 160 °C; however, all camera operations failed during the cool down period. Throughout the heated period, the camera image remained clear with no degradation. Near the end of the thermal exposure, after 12.75 min, the “high temperature” warning appeared on the camera screen. There was no degradation of the image, and the camera continued to operate properly and deliver a clear picture for the last few minutes of the Class II test. The camera was then allowed to cool, and approximately 5 min into the cool down period, the camera stopped working. As with camera 2, there was no degrading of the image; the display just abruptly went dark. During the inspection of the camera after the test, it was noted that the battery remained very warm, while the rest of the camera was at room temperature. The camera was allowed to cool for three days. A new battery was supplied to the camera, but it did not regain operation following this test.

Beyond Thermal Class II

Before testing at the Thermal Class III conditions, an intermediate test was performed on Camera 1 by subjecting it to a 5 min thermal exposure at 210 °C. The camera functioned perfectly throughout this test. The image on the camera display was unchanged throughout the test and the cool down. Following cool down, the camera was inspected, and there was no observable melting, deformation, or any damage to any parts of the camera, except for the battery. The casing of the battery had melted slightly and had become warped. Inspection of the insides of the battery housing area showed no internal damage, including no damage to any of the exposed electronic components in this area. A new battery was supplied to the camera and the camera operated properly with this battery.

Camera 1 was then tested at the Thermal Class III condition of 260 °C exposure for 5 min. This camera survived the 5 min exposure with no changes in the display and no degradation of the picture; however, it failed immediately afterwards during the cool down. Approximately 45 s into the cool down, the top edges of the screen began to darken. The darkening of the screen continued over the next 120 s, working from the edges to the interior until the entire image was gone. Figure 8 shows a picture taken 80 s into the cool down, with darkening of the screen visible in the upper right hand corner (compare with Figure 2). After cool down, an inspection of the camera revealed that the casing of the battery had melted and deformed. Other than the warping of the battery case, there was no other observable melting, deformation, or damage of any kind to any other parts of the camera. The battery housing area was inspected and showed no internal damage. A new, fully charged battery was then supplied to the camera; however, camera operation did not recover.

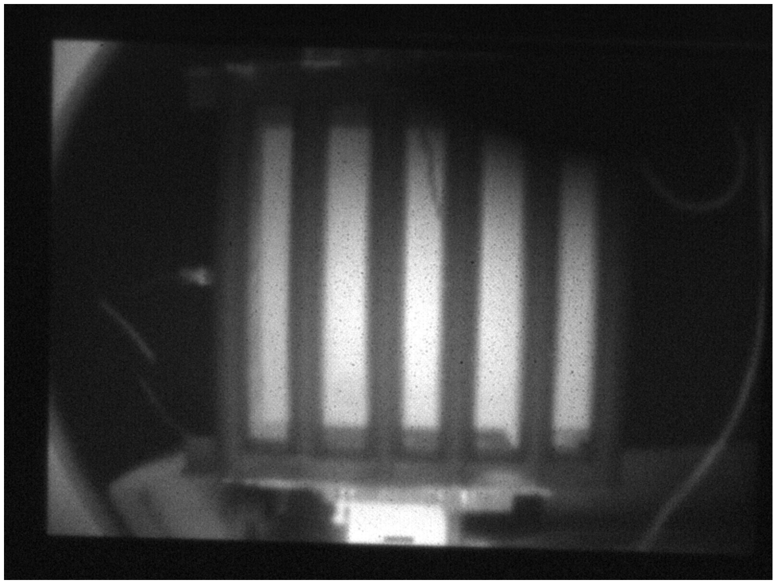

Figure 8 Photograph showing the screen of TIC 3 darkening just before failure.

Results Summary

A summary of the results of this preliminary testing is shown in Table 2. All three cameras tested were able to withstand the exposure to Thermal Class I conditions, with no observable damage and no impairment of camera operation. After the Thermal Class II exposure; however, only one of the three cameras was functional. One camera stopped working after a few minutes at the Class II temperature, and another camera failed during the cool down period. The third camera survived the 5 min at the Class III temperature of 260 °C, but stopped working shortly afterwards during cool down. In all cases, once the camera had stopped working, the failure was permanent. Operation was not restored after the camera had cooled and the battery was replaced.

Table 2 Results Summary

Camera	Temperature	Time	Image during soak	Cool Down	Observations
Camera 1	100 °C	25 min	Clear Image	Operates properly	No damage
Camera 2	100 °C	25 min	Clear Image (battery indicator operated erratically but the image remained good)	Operates properly.	No damage
Camera 3	100 °C	25 min	Clear Image	Operates properly	No damage
Camera 1	160 °C	15 min	Clear Image	Operates properly	No damage
Camera 2	160 °C	2 min 48 s	Failure - no image after time indicated	Camera has failed	No operation with new battery
Camera 3	160 °C	15 min	Clear Image	Camera fails during cooling	No operation with new battery
Camera 1	210 °C	5 min	Clear Image	Operates properly	Battery warped, Operates properly with new battery
Camera 1	260 °C	5 min	Clear Image	Camera fails during cooling	Battery warped, No operation with new battery

Discussion

The three TICs tested, though similar in description, exhibited different abilities to withstand elevated temperatures. These tests showed that at least some of the TICs currently on the market are susceptible to failure at thermal conditions experienced in firefighting. The lack of standard performance metrics has resulted in a huge difference in the temperature tolerances of the cameras. The outer casings withstood the high temperature assaults with no warping or other damage; however, heat transfer to the inner workings resulted in eventual failure of TIC operations.

The inclusion of a "high temperature" warning that was present in one of the cameras is a useful feature since it was the only indication of impending camera failure for that particular camera. The other cameras had no warning mechanism for failure due to high temperatures.

Prior to this testing, we did not have any knowledge of the camera behavior at elevated temperatures. The temperature target was prepared with the expectation that the TIC display screen images would experience some type of degradation or loss of sensitivity, possibly followed by camera failure. The target was designed to allow for evaluation of the images and any picture degradation to be quantified. When the tests were conducted, it was found that the display screen images remained clear up to the point of complete failure. Any possible image degradation during these tests was not visible to the naked eye, and was deemed negligible for the purposes of this evaluation. TIC 1 did experience darkening around the edges before the display stopped working.

Both Thermal Class I and Thermal Class II represent conditions where search and rescue, and identification of hot spots would likely be conducted using TICs. The fact that one of the three TICs tested was capable of surviving Thermal Class II conditions suggests that it is technically feasible to consider Thermal Class II conditions when developing a standard for TICs.

CONCLUSIONS

These preliminary tests on a limited number of TICs revealed some basic findings about camera operation at elevated temperatures.

1. All TICs tested operated properly throughout the Thermal Class I temperature exposure.
2. Only one of the three cameras continued to function after Thermal Class II exposure.
3. The failure mode for each of the TICs was due to loss of the display screen image. In two cases the display image failure was abrupt, and in the third case the screen slowly darkened over the course of about two minutes.
4. For these three cameras, operational failure was permanent. Once the cameras stopped working, operation could not recover by cooling the camera or replacing the battery.
5. There was no observable melting, warping or damage to the outer casings of the TICs at the conditions where the inner components were damaged.
6. The thermal classes developed in an earlier paper worked well in quantifying the performance of the three TICs and could be considered as a basis for developing industry-wide standards for these devices.

Future Directions

For this set of experiments, heat was the only component of the fire environment that was investigated. Other components of the fire environment, such as smoke, chemicals or water vapor can impact the operation of electronics. If the instrument casings or seals of the TICs are compromised due to heat, then it may be possible for smoke, chemicals or water vapor to penetrate and interfere with the camera operation. These preliminary results showed no observable breaches in the outer casings, but further testing is needed to verify that the cameras can survive these additional insults.

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