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Meaningful performance evaluation conditions for fire service thermal imaging cameras

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Abstract

Thermal imaging cameras (TIC) are rapidly becoming integral equipment for the fire service for use in structure fires and other emergencies. The Building and Fire Research Laboratory (BFRL) at the National Institute of Standards and Technology has conducted research to establish test conditions that best represent the environment in which TIC are used. Firefighters may use TIC for field operations ranging from fire attack, search/rescue, hot spot detection, overhaul activities, to detecting the location of hazardous materials.

To develop standardized TIC performance metrics and test methods that capture the harsh environment in which TIC may be used, information was collected from users, the literature, and from fire tests conducted at BFRL. A workshop was held to facilitate knowledge transfer from the fire service and TIC manufacturers. Full-scale and bench-scale experimental work focused on temperature extremes and the presence of obscuring media such as smoke, dust and water. Consolidation of fire environment data with fire fighting operations and imaging needs resulted in a set of performance metrics and test methods that relate to the conditions and tasks encountered by firefighters in structural fire fighting applications. This work is included in a new draft standard on fire service TIC.
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Keywords: Evaluation; Firefighter; Fire service; First responder; Infrared camera; Standards development; Test conditions; Test methods; Thermal imaging camera

1. Introduction

Over the past several years, the Fire Research Division at the National Institute of Standards and Technology has been conducting research on thermal imaging camera (TIC[1]) imaging performance metrics and test methods with the overall objective of providing science-based information to national standards developing organizations. The National Fire Protection Association (NFPA) is currently developing the Standard on Fire Service Thermal Imaging Cameras, Draft NFPA 1801 [1], and the American Society of Testing and Materials (ASTM) is revising a test method on infrared detector sensitivity, ASTM E1543-00 [2]. Both of these organizations are using NIST-generated technical results as their standards are being developed. Although a plethora of generally accepted performance metrics and test methods exists for infrared cameras used in other applications, such as those used in laboratories and for preventative maintenance operations in buildings, they fail to consider the effects of the harsh environment in which TIC are used by the fire service. The challenges imposed by this environment and by the needs of firefighters necessitate new or modified performance metrics and test methods to ensure that TIC performance is adequately addressed.

In this study, a survey of available information on TIC operating environments is provided and test conditions are recommended that relate to fire service applications. There are two ways in which operating conditions affect TIC: first, the camera itself must be rugged enough to function in

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[1]The acronym TIC shall be used throughout this text in reference to both the singular and plural forms, i.e., thermal imaging camera(s), as befits the context of the sentence in which it is used.

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elevated temperatures and humidity, and other adverse conditions, and second, the camera must be capable of producing images that provide useful information to the user. Functionality tests address the ability of the TIC to operate in a harsh environment. Image quality tests address the ability of the TIC to capture a scene with sufficient sensitivity and detail to enable the user to perform a particular activity such as searching for a fire victim. The performance needs associated with both of these activities are considered in this study in terms of the operating environment.

An important step in the process of developing a meaningful performance standard for TIC is to establish test conditions that adequately represent the gamut of environments in which these cameras are used. Firefighters may use TIC for field operations ranging from searching for a hidden fire source, to directing a hose stream, to detecting the location of hazardous materials. New uses for TIC are being discovered as they become more widely used in the fire service community. At one boundary of the range of conditions in which the imaging performance of TIC is challenged, open flames and water-coated surfaces may be seen in the same field of view (FOV). At the other boundary, the ability to see very slight differences in temperature and/or emissivity may be required to discern the level of contents of a chemical drum at near-ambient temperature. Whereas it is relatively simple to capture the essence of the latter test condition in a laboratory setting, the former scenario, along with other conditions related to fire fighting, can be much more challenging and, therefore, are given particular attention in this study.

The environment encountered by firefighters varies, depending on the nature of the fire scenario. Decades of fire testing have shown that the gas temperature in a naturally ventilated burning room stratifies, due to buoyancy, into a hot upper layer that contains combustion byproducts and a cooler lower layer composed mainly of ambient air. The time-varying severity of conditions in the room of fire origin and adjacent or nearby rooms will change depending on the type and amount of materials burning, thermal properties of the room surfaces, the ventilation conditions, the size of the room, and a number of other factors [3]. As any firefighter will gladly explain, no two fires are exactly the same.

2. Approach

The objectives of this study have three parts: first, assess the various TIC uses and needs of the fire service; second, determine a representative range of conditions in which TIC are used by firefighters; and third, define a representative set of environmental conditions to use during TIC functionality and image quality testing.

This work began with an assessment of the thermal imaging needs and activities of firefighters. To facilitate the gathering of this information, a workshop on Thermal Imaging Research Needs for First Responders was held at NIST in December 2004. Ties were established between industry, the first responder community, and NIST that have, over time, helped shape the Draft NFPA 1801 standard and accelerated the somewhat protracted standard development process.

Existing standards were collected and reviewed to ensure that the recommended testing conditions in this work are consistent with standards on other fire fighting equipment in terms of exposure to operating conditions. In addition, the standards and test protocols for infrared cameras used in other applications were consulted for possible application. A survey of the literature was also performed to explore existing research in which the fire environment was well characterized and pertinent to TIC testing.

Several series of full-scale tests were conducted at BFRL's Large Fire Laboratory. Attention was focused on TIC performance under conditions of temperature extremes and in the presence of obscuring media such as smoke. Image quality in the presence of open flames and different types of hose streams was also tested for a limited number of TIC. These tests helped bracket the thermal conditions to which TIC are exposed and also provided design guidance for bench-scale test development. Lastly, all of this information was reviewed, compared, and used to define a set of testing conditions for TIC functional tests and image quality tests.

3. Discussion

3.1. User input

Before operating conditions are discussed, it is instructive to list the ways that TIC are currently being used in the field. This information is provided in Table 1. From this, one can estimate the thermal and spectral environments which impact the functionality and imaging performance of TIC. Table 1 is not a comprehensive list; it was compiled from input from a variety of users and is changing and expanding as the fire service community increasingly accepts TIC technology and discovers the value of these tools through shared stories of successful operations in which TIC played a critical role. Clearly, not all firefighters use TIC for every activity listed in Table 1. Each fire service organization has its own set of operational procedures and needs.

Accounts, in which TIC have been credited with making direct contributions toward saving the lives of victims and firefighters, can be found in news stories such as the 1999 incident in Franklin, IN, where a 2-year-old boy was rescued from a residence fire [3]. A TIC was used to size up fire conditions in a Ruckersville, VA structure fire, causing the incident commander to modify his strategy for entering the building. Without the TIC, the incident commander stated that fire investigators following the standard entrance procedure might have walked into a very dangerous backdraft condition [4]. Other discreet examples of how TIC were successfully used to identify hazardous

Table 1
Fire service TIC operations

Activity	Description
Size up	Assess hazard, find fire/heat sources, escape points, and vents
Communication	Lead or direct searches, interface with incident command, account for team members
Search	Locate victims, other firefighters, fugitives, missing persons in dark and/or smoky environments
Tactics	Direct hose stream, check upper layer temperature, check for changing conditions, detect obstacles, passageways, damaged structural members, judge distances, use in rapid intervention teams
Overhaul	Ensure fire is out, look for hidden smoldering and hot spots
Forensics	Identify source of fire, determine fire spread, record video during fire for later use as evidence
Wildland fires	Ground- and air-based search for hot spots and personnel
Hazmat	Determine material levels inside containers, track material movement and spill spread limits
Other	Preventative building maintenance, emergency medical applications, motor vehicle accident investigations

materials, the cause of "smell of smoke" calls, and conditions that affect structural integrity are given in Ref. [5]. The firefighters Save A Life Fund website hosts numerous accounts of events that attribute their positive outcome to the use of TIC [6].

A quantitative understanding of TIC performance for a range of possible operating conditions would be of potential benefit for purchasing and tactical aid decisions. Due to tradeoffs in the design of a TIC, it is unlikely that a single TIC will perform better than its competitors for every type of operation. For example, TIC "A" might be optimized such that it can discern thermal details relatively well when flames are in the FOV, but it may not provide adequate thermal sensitivity at ambient temperatures to determine the level of a chemical in a container. On the other hand, TIC "B" may not produce sharply defined images in any of the above-listed situations, but may be much less expensive and still have value for directing hose streams toward a fire source. The needs of the fire service may be best served when they are confident that a TIC has been rigorously tested, will not fail under adverse conditions, and the images produced by a TIC are of a sufficient quality for their particular mix of activities.

3.1.1. Workshop on Thermal Imaging Research Needs for First Responders

The Workshop on Thermal Imaging Research Needs for First Responders was held at NIST in December 2004 in order to better understand the needs of users, manufacturers, government agencies, and other proponents of TIC technology and to identify barriers that impede advances in the application of thermal imaging technology to emergency response. This workshop provided a forum to discuss the strategies, technologies, procedures, best practices, research, and development that can significantly improve thermal imaging technology for the first responder community. After hearing presentations, the workshop divided into three breakout sessions to discuss and prioritize issues relating to the following four questions:

1. What technological advances are needed?
2. What are the research needs for first responders?
3. What performance metrics are needed and how do they differ from current methods?
4. What standards are needed?

The issues that were found to be most important to the attendees of the workshop are shown in Fig. 1. The workshop proceedings are available at http://fire.nist.gov/bfrlpubs/fire05/PDF/f05036.pdf [7].

An important result of the workshop was the formation of a follow-on group of TIC manufacturers and fire service personnel who began meeting regularly to devise an approach for standardizing the TIC user interface. This group grew to include representatives from all the US manufacturers of TIC and TIC detectors. Eventually, the image quality work described herein was combined with the user interface results of the follow-on group, resulting in a draft document that has been accepted in principle by the NFPA Technical Committee on Electronic Safety Equipment as a basis upon which to proceed with the Draft NFPA 1801 Standard on Thermal Imaging Cameras for Emergency Services [1].

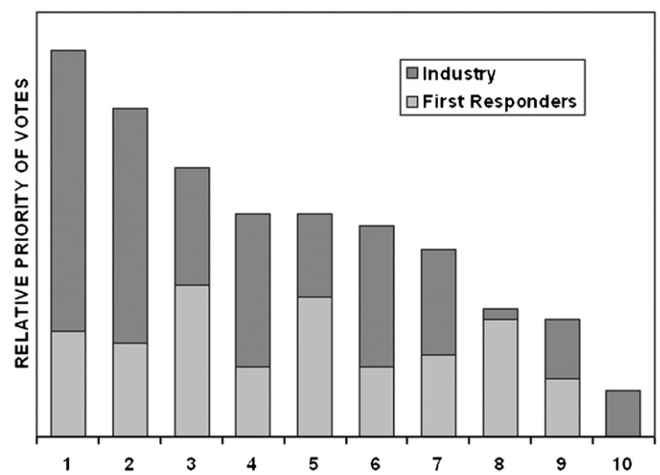

Fig. 1. Thermal Imaging Research Needs, as indicated by participants of the Workshop on Thermal Imaging Needs for First Responders in December 2004. Key for item numbers in abscissa: (1) image quality (research, metrics, standards, contrast, sensitivity); (2) durability (metric, mean time between failures, standard test methods for ruggedness); (3) training and certification for users; (4) establish minimum/typical test environments; (5) human factor/ergonomic and human dynamics research; (6) image display (technology, viewability, metrics); (7) battery and charger (life/maintenance, icons, and self-test improvements); (8) reduction in imager cost ("water bottle"-sized package priced at $2K); (9) standard target (for field test/calibration and emissivity target for turnout gear); (10) imager self-test procedure and warning system.

In addition to hearing directly from stakeholders about their TIC research needs, information about fire environments and other operating conditions was also collected from the literature, from existing standards for other personal protective equipment, from internal test reports, and from full-scale and bench-scale testing. Additionally, in order to gain firsthand experience on the use of TIC in burning buildings, some NIST personnel underwent training through a professional TIC training course[2,3] for first responders. Direct communication between the fire service and NIST personnel regarding the use of TIC and the environment in which they are used is ongoing and will continue as this work progresses.

3.2. Survey of relevant standards and work by others

A literature search was performed to find information on operating conditions that correspond to the TIC activities discussed in the previous section. In this section, existing standards that relate to the development of a TIC performance standard are discussed. Additionally, existing research is presented that reports information on the thermal environment in which TIC may be used.

3.2.1. Existing standards

There are several standards development organizations that write standards on electronic and other personal protective equipment used by the fire service, and standard test methods do exist for TIC used in non-emergency service applications, but there is currently no standard specifically written for TIC used by the fire service.

The following is a brief discussion of some details of existing standards, which may have bearing on TIC operating conditions for functional and image quality tests. American National Standards Institute (ANSI) standard ANSI/ISA-12.1201 covers intrinsic safety testing for non-incendive devices [8]. Several ASTM standards are functional tests for exposure to salt spray [9], transmittance of lens [10], flame resistance [11], and liquid penetration [12]. There are also several ASTM test methods for infrared camera image quality [2,13–17]; however, these test methods do not include extreme operating environments in their tests. Pertinent publications from the International Standards Organization (ISO) include enclosure integrity [18], electromagnetic compatibility [19], functional safety [20], and resolution measurements for still cameras [21]. The Military Standard, MIL-STD 810F, tests resistance to mechanical acceleration [22]. Underwriters Laboratory (UL) produces a large number of standard test methods for many aspects of design for electrical and electronic devices such as proper grounding and wiring for switches and terminal blocks. The Video Electronics Standards Association (VESA) writes standard test methods for measuring display performance [23]. In addition to the above standards, which are not specifically written for fire service equipment, NFPA produces standards on communications systems [24], protective clothing for structural firefighting [25], protective clothing for wildland firefighting [26], self-contained breathing apparatus [27], and personal alert safety systems [28], which are intended for equipment that might be exposed to thermal environments similar to those experienced by TIC. Note that there are only two NFPA standards, on self-contained breathing apparatus and on personal alert safety systems, which are written specifically for electronic devices used in burning structures. Firefighters sometimes use electronic gas detectors, but these devices have no formal standards for operation or functionality, although some adhere to the ANSI/ISO standard on non-incendive devices. Currently, some TIC manufacturers voluntarily adhere to some of the standards discussed here, but are not required to do so.

3.2.2. Relevant work by others

Recent work by Donnelly et al. [29] recommends the concept of thermal class to systematize functional tests on fire service electronic equipment. The recommendations are based on tests performed by several groups of researchers. The thermal classes are reproduced in Table 2.

The thermal class categorization system is a constructive method of representing the increased risk to firefighters related to the thermal environment. The most prevalent use of TIC would be in the first three thermal classes. Systematic use of a TIC in response to the fourth and most severe class of fires is unlikely as not enough time would be available under such hazardous conditions, however, brief exposure may occur as a firefighter retreats from impending severe conditions. In addition, the current generation of TIC tends to be saturated under such conditions, negatively impacting their effectiveness, although future generations may overcome this problem. It is expected that trends in visibility conditions scale with thermal class. For example, it is expected that less smoke is associated with a smaller Class I fire situation than a larger Class II or Class III fire.

Consideration of test results from various compartment fire experiments helps broaden our understanding of the range of visibility and imaging conditions that a firefighter

Table 2
Thermal classes (Donnelly et al.)

Thermal class	Maximum time (min)	Maximum temperature (°C)	Maximum heat flux (kW/m^2)
I	25	100	1
II	15	160	2
III	5	260	10
IV	<1	>260	>10

[2] See SAFE-IR, http://www.safe-ir.com/.

[3] Certain commercial entities, equipment, or materials may be identified in this document in order to describe an experimental procedure or concept adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the entities, materials, or equipment are necessarily the best available for the purpose.

may encounter. For evaluation of the performance of TIC, the concentration of smoke and possibly some gas species must be considered. Unfortunately, the understanding of the generation of smoke from a fire is incomplete. In a compartment fire burning realistic materials, the smoke generation rate (smoke yield per unit fuel mass) is difficult to predict to within a factor of six, even for relatively simple fuels [30]. The smoke produced will increase with the fuel mass burning rate and the fire heat release rate, so, generally, the smoke concentration can be expected to increase with the thermal class categories listed in Table 2 as fire grows and spreads, and a hot upper layer develops.

A typical situation in which a TIC is used may involve a residential or commercial fire, where furnishings, structural materials, electrical appliances, or other materials burn in a flaming or smoldering mode. Many common commodities are composed of either cellulosic or thermoplastic materials. As these commodities burn, smoke and combustion byproducts, such as carbon dioxide (CO_2) and water (H_2O), will be produced in large quantities. Although much fuel mass is converted to CO_2 and H_2O, a significant percentage can go to the production of smoke, varying from about 1% to 20% by mass, depending on the fuel type [31]. Smoke (or soot) is a product of incomplete combustion and is not a gas, but is instead a complex solid particulate whose form and concentration depend on the type of fuel and the ventilation conditions within the compartment. Once formed, it is transported with other combustion products, first within a compartment and then beyond the room of origin. In actual fires, trace combustion species (e.g., HCN, C_2H_4, C_2H_6) may also be formed [32,33]. These species are relevant to TIC performance because they may be optically active in the infrared portion of the spectrum, from 8 to 14 μm, which is employed by TIC. In practice, these species may (or may not) negatively impact a TIC in realistic applications, as the combination of concentration and band intensities may (or may not) be significant. The measurements reported here investigated this issue for the burning of common household materials.

Several full-scale compartment fire experiments in the scientific literature provide information on conditions in enclosure fires, such as those that may be encountered during fire-fighting operations. This information is relevant when considering the performance of TIC. Table 3 summarizes some of these results, listing the fire heat release rate ($\dot{Q}$), the peak upper layer gas temperature, and the peak concentration of smoke in the room of fire origin. In the experiments listed in the table, the fire was ignited and a hot upper layer developed as noted by increasing values of temperature and smoke density. If the fires were controlled or prescribed, quasi-steady state conditions may have occurred in the upper layer, provided that the fires burned for a sufficiently long duration. Empirical correlations have been derived that relate the hot gas layer temperature and species to the heat release rate. As a fire spreads and grows through an enclosure or building, the hot upper layer in a severe fire can reach temperatures and smoke concentrations as high as 1000 °C and 20 g/m^3, respectively. In a fire that is not prescribed, the heat release rate depends on naturally occurring fire spread and growth. In that case, the time rate of change of the room conditions depends on the fire heat release rate, the fuel type, the ventilation, the room size, and a number of other parameters.

3.3. Full-scale experiments

Several series of full-scale fire experiments were conducted at BFRL's Large Fire Laboratory specifically to investigate TIC performance under repeatable and controlled conditions. The primary objective of these tests was to characterize the image quality of the TIC and the way it relates to the thermal environment. In these tests, a selection of fire service TIC, scientific TIC, and visible cameras were trained on infrared targets, which were placed either in the room of fire origin or in a corridor adjacent to the room of fire origin. Firefighters may operate within the room of fire origin or in adjacent spaces

Table 3
Peak conditions measured during typical compartment fire experiments

Reference	Thermal class	Heat release rate, $\dot{Q}$ (kW)	Fuel type	Peak temperature (°C)	Peak smoke density (g/m^3)
[35]	IV	1000 (peak)	Furnishings	1100	1[a]
[36]	III	200 (peak)	Furnishings	nr[b]	20
[37]	IV	3000	Heptane/toluene[c]	540	2
	IV	3000	Heptane	500	0.3
[38]	III	1000	Toluene	200	0.4
[39]	IV	100	Natural gas/acetylene[d]	660	nr
[40]	IV	600	Natural gas/wood[e]	950	nr

[c]Liquid mixture of 60% heptane and 40% toluene (by mass).
[d]Gaseous mixture of 76% natural gas and 24% acetylene (by mass).
[b]nr: not reported.
[a]An optical density (D/l) of 5 m^{-1} was reported. The value of D/l is related to the smoke density (C_s) and the specific extinction coefficient of smoke (ξ) by $C_s = (D/l)/\xi$, where ξ is typically on the order of 5 m^2/g [31].
[e]Natural gas burner below wood-lined ceiling.

for Class I, Class II, and Class III conditions, and may use TIC with a Class IV environment in the FOV. Temperature, gas, and smoke measurements were conducted both within the room of fire origin and in the adjacent spaces. In some tests, two identical infrared targets were placed at the end of the corridor and positioned such that the TIC could view a target in the upper or lower layer. A representative schematic of the test layout is shown in Fig. 2.

The distance from the TIC lens to the target (the sight distance) was 3, 6, and 12 m. In Table 4, the fire heat release rate and the peak CO_2 volume fraction, peak temperatures, and smoke concentrations that were measured in the line of sight between the TIC and the infrared targets are reported. Volume fractions of CO and O_2, and emission spectra were also collected. In some cases, these measurements were made in the room of origin and in some cases, they were made in the adjacent spaces, where a firefighter would have been operating (see notes in Table 4). Methanol fires with heat release rates ranging from 50 to 350 kW were used to isolate the effects of elevated temperature and the presence of gaseous combustion products on image quality, as this fuel produces essentially no smoke. Tests were conducted in which methanol fires were placed between the TIC and the target, and within the camera's FOV, but not directly in line with the target. Heptane, propylene, and toluene fires were used to examine the effects of different smoke concentrations and upper layer temperatures on image quality. Dust, steam, and hose streams having different spray characteristics were used to test the effects of non-fire operating conditions on TIC image quality.

Fire tests were also conducted in which materials that represent realistic fuels were used. For these tests, wood cribs were burned alone or with nylon carpet and urethane carpet padding. Urethane cushions with polypropylene covers were also used as a fuel source. In all cases involving realistic materials, the TIC were positioned to look along a corridor, which was adjacent to the room of fire origin similar to the layout shown in Fig. 2, toward a thermal target placed on a wall at the end of the corridor. The TIC were rotated through a sequence of positions during each test such that each TIC viewed the target through the lower layer and the upper layer for sight distances of 6 and 12 m (see inset in Fig. 2). The width of the hot/cold bars in the infrared targets was 10, 7.5, and 5.0 cm. This target design tested the ability of TIC to discern detail. In addition to the bar targets, a heated mannequin fitted with firefighter turnout gear was placed on the floor at the end of the corridor and was used as a more realistic target.

Temperatures were measured using Type K, 24-gauge thermocouples arranged vertically at 0.3 m intervals in a "tree" formation. The CO_2 volume fraction was measured using a Siemens Ultramat 6 gas analyzer. The smoke

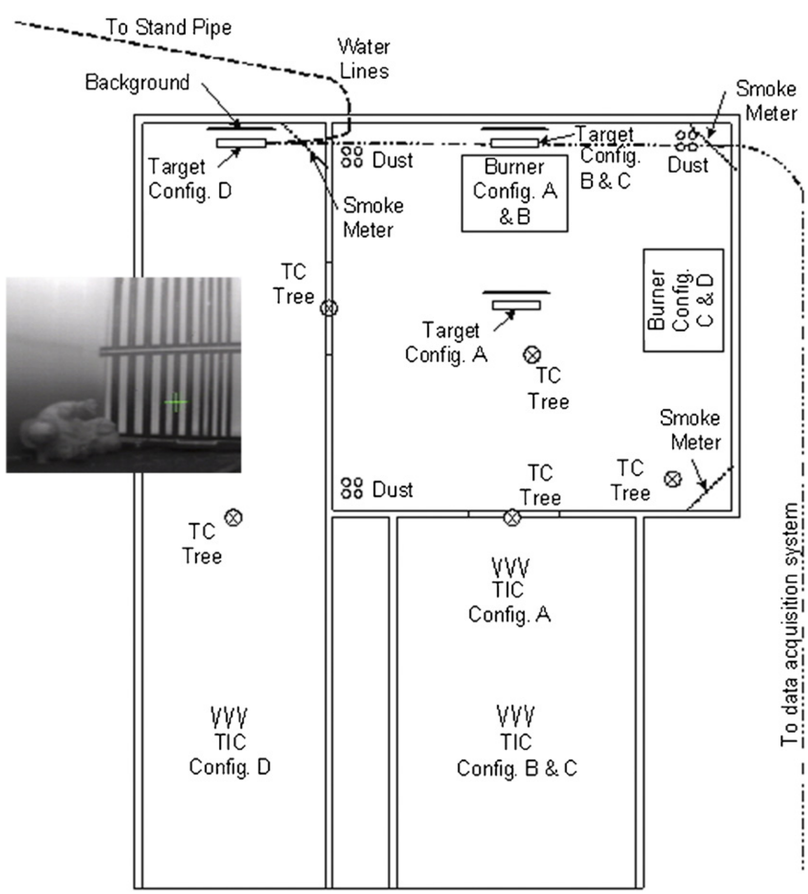

Fig. 2. Plan view of representative full-scale fire test layout with instrumentation and inset showing upper and lower thermal bar and mannequin targets.

Table 4
BFRL experimental results

Heat release rate, $\dot{Q}$ (kW)	Fuel type	Peak CO_2 concentration (vol%)	Peak temperature (°C)	Peak smoke density (g/m^3)
200	Methanol	nr	191 (±3%)[a]	0.04 (±10%)[a]
200	Heptane	nr	203[a]	0.10[a]
175	Heptane	nr	180[a]	0.11[a]
175	Toluene	nr	140[a]	0.76[a]
175	Heptane	nr	190[a]	nr
12–21	Propylene	nr	83[a]	0.14[a]
33	Propylene	0.5 (±10%)[b]	62[c]	0.15[c]
200	Toluene	2.9[b]	141[c]	0.46[c]
175	Toluene	nr	123[c]	0.45[c]
350	Methanol	5.9[b]	220[c]	nr
200	Methanol	nr	184[c]	0.1[c]
100	Methanol	nr	128[c]	0.1[c]
50	Methanol	0.6[b]	56[c]	nr
300 (peak)	Double wood crib	6.5[b]	150[c]	nr
200 (peak)	Single wood crib	2.0[b]	110[c]	0.01[c]
600 (peak)	Cushions	5.7[b]	142[c]	0.75[c]
nr	Wood crib over carpet and padding	9.3[b]	200[c]	0.58[c]

[a]Average peak temperature and smoke density values measured in room of fire origin.
[b]Average peak CO_2 concentration measured in corridor adjacent to room of fire origin.
[c]Average peak temperature and smoke density values measured in corridor adjacent to room of fire origin.

concentration was measured gravimetrically by drawing a known volume of smoke-laden gas through a filter.

3.3.1. FTIR measurements

The intervening media between a target and an imager may impact the view of a TIC through emission, absorption, or scattering. The current generation of commercial TIC detect in the mid-infrared region of the spectrum from wavenumbers of about 700–1250 cm^{-1} (wavelengths 14–8.0 μm). This region is selected because radiant emission intensities for radiating objects is large enough to detect in this region and there is minimal overlap with the spectra of the most common combustion species with the exception of smoke. The experiments sought to answer the question, "does the spectral response of TIC vary for different technology types, and is imager performance differentially affected by the presence of a hot layer of combustion products including smoke?"

The impact of an intervening smoke aerosol on an imager's view depends on its temperature and its concentration as compared to the temperature and emissivity of a target. Smoke may absorb and scatter, but will not emit a significant intensity of radiation if its temperature is relatively cool. In a typical compartment fire, smoke may obscure human visibility. The value of the smoke mass-specific extinction coefficient decreases with increased wavelength, and in the infrared, attenuation by smoke decreases with wavelength, allowing TIC to "see" through smoke [34].

Chemical compounds that give rise to a dipole moment absorb and emit infrared radiation at unique and characteristic frequencies. In the experiments reported here, a portable Fourier transform infrared spectrometer (FTIR) was used to characterize the line of sight-radiative emission in the infrared, from 650 to 5000 cm^{-1} (15.4–2.0 μm), covering the entire spectral range of a typical TIC. The FTIR was positioned outside the corridor and was aligned to detect the same bar target that the TIC were positioned to view, looking through the hot upper layer of the 12 m corridor. The measurements were made at 0.5 cm^{-1} resolution, which resulted in a sampling rate of about 1 scan/s. The measurements were stored as averages of 60 scans, or 1 min of data. The FOV was collimated, covering on the order of 5 cm at the 12 m sight distance.

Fig. 3 shows the measured relative radiant intensity as a function of wavenumber during an experiment in which the burning fuel source was a wood crib over carpet and padding (see the last entry in Table 4). FTIR results are shown at 0 and 4 min after ignition in the experiments. The relative FTIR signal increased significantly with time. Table 4 shows that the upper layer temperature in the experiment obtained a peak value of about 200 °C, which occurred about 4 min into the experiment. The upper layer temperature at 4 min suggests that the experiment was a Class III thermal condition at that time (see Table 2). At early times in this experiment and for some of the other experiments, Class I and Class II conditions were tested. The FTIR measurement of a blackbody source at 200 °C (with a standard absolute uncertainty of ±5 °C based on an estimate of measurement accuracy) is also shown in Fig. 3, which is consistent with the experimental spectrum. This suggests that the smoke was optically thick in the hot upper layer of the corridor. Band absorption by water vapor is seen at wavenumbers between about 1300 and

2000 cm^{-1} (7.7 and 5.0 μm). The figure also shows recognizable emission signatures for individual species during the experiment, but not in the spectral region in which TIC are sensitive, reinforcing the reason fire fighting TIC are designed to operate in this portion of the infrared spectrum. The results for the experiments burning the other fuel types yielded similar results, as little band radiation was observed in the portion of the spectrum in which the TIC are sensitive, thus indicating that fuel type is not a dominant parameter when testing TIC imaging performance for typical smoky fuels.

3.5. Consolidation of test condition information

In keeping with the thermal classification approach, the TIC activities listed in Table 1 can be categorized (with some overlap) into three of the four classes given in Table 2. The test results reported in Tables 3 and 4 provide guidance as to the nature of the thermal environment that might be encountered, while performing fire-fighting activities. Existing standard requirements for functionality tests are embedded in the development of the four thermal classes, e.g., a TIC used in a Class III environment should be able to function properly under the same conditions in which firefighter turnout gear is tested (withstand temperatures up to 260 °C for 5 min per NFPA 1971 [25]).

With respect to image quality testing, there are distinctly different imaging needs for each of the thermal classes, with respect to both the environment and the TIC user's activities. This is evident in Table 5, where a firefighter or other first responder may use a TIC in an environment that generates relatively low thermal signals (Class I) to perform operations that may depend on a strong signal to noise ratio, therefore, measurements of thermal sensitivity (ability to measure a thermal signal) and non-uniformity (ability to keep broadband noise to a minimum) are appropriate. Thermal sensitivity and non-uniformity are very dependent on the thermal environment and are, therefore, measured in each of the thermal classes. Conversely, spatial resolution is a measurement of the TIC's ability to see spatial detail and is not a direct function of the thermal environment. Since spatial resolution is not directly related to thermal class, it is recommended that this parameter be tested in a Class I environment, due to the ease of testing in this class relative to others.

In a Class II environment, one in which firefighters spend significant amounts of time, TIC may view a wide range of surface temperatures, as well as water and flames, or other very hot surfaces. In this case, the challenge to the TIC is related to dynamic temperature range. The measurement of the TIC's ability to maintain contrast and provide sufficiently resolved images, particularly in discerning intermediate temperature differences when extreme surface

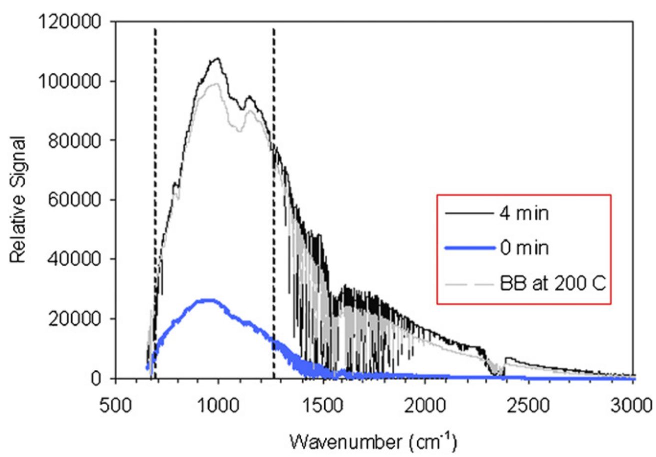

Fig. 3. The relative FTIR signal measured at two times during an experiment burning carpet, padding, and wood. For comparison, measurement of the relative signal of a blackbody source at 200 °C (±5 °C) is also shown.

Table 5
Proposed TIC testing conditions

Class	Class I (water, fog, or snow possible, minimal heat, smoke and flames)	Class II (elevated temperatures, water, dust, smoke and flames may be present)	Class III (high temperatures and smoke concentrations, flames, dust and water are likely)
Activity	Hazmat Medical Motor vehicle accident Search	Overhaul Size up Forensics Preventative maintenance Search	Overhaul Forensics Wildland fires Size up Tactics Communication Search
Proposed test	Spatial resolution Thermal sensitivity Non-uniformity	Contrast Effective temperature range Thermal sensitivity Non-uniformity	Thermal sensitivity Non-uniformity

Note: TIC would not likely be used in a Class IV thermal environment. Firefighters operating in Class IV thermal conditions would be in retreat, rather than viewing the scene through a TIC, although one might reasonably expect to view a Class IV scene from a distance.

temperatures exist in the FOV, are key performance metrics included in the NFPA 1801 Draft Standard.

A Class III environment presents yet a different type of challenge for a TIC. In this case, everything in the FOV is hot, which can saturate the TIC detector (too much signal) and induce significant broadband noise. Thermal sensitivity and non-uniformity measurements are the appropriate means to evaluate TIC image quality in this environment and are part of the suite of recommended performance metrics in the NFPA 1801 Draft Standard.

4. Conclusions

In this study, relevant information regarding the establishment of conditions under which to test the performance of TIC has been assembled with the objective of developing test conditions, which are relevant and representative of fire service operations. Input from users, as well as existing standards, research reports, and test measurements were considered in the development of representative TIC performance testing conditions. The concept of thermal class as a means of categorizing the activities in which TIC are used by firefighters is helpful in defining meaningful bounds on TIC test conditions. The four thermal classes link the various requirements of existing standards on related fire service equipment with experimental results from full-scale testing and the scientific literature.

The upcoming NFPA 1801 Standard on Thermal Imaging Cameras for the Fire Service will address functionality test conditions. The recommended TIC image quality testing conditions are the product of matching TIC operations with the thermal environment in which they are used. The test conditions reflect the need to see spatial detail (spatial resolution), thermal detail (thermal sensitivity), and contrast within a wide range of surface temperatures, without significant image degradation due to broadband noise (non-uniformity).

The type of fuel used in full-scale fire experiments was found not to be an important parameter with respect to TIC imaging performance. Radiation emitted from very smoky, poorly characterized fuels, such as a burning wood crib with carpet and padding, does not significantly impact the spectral region employed by fire service TIC.

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References

[1] Proposed NFPA 1801: Standard on Thermal Imagers for the Fire Service, 2009 Edition, National Fire Protection Association, Quincy, MA, 2007.
[2] ASTM E 1543-00 (2006) Standard Test Method for Noise Equivalent Temperature Difference of Thermal Imaging Systems, ASTM International, West Conshohoken, PA, 2006.
[3] M. Bundy, A. Hamins, E.L. Johnsson, S.C. Kim, G.H. Ko, D.B. Lenhert, Measurements of heat and combustion products in reduced scale ventilation limited compartment fires, NIST Technical Note TN 1483, National Institute of Standards and Technology, Gaithersburg, MD, 2007.
[4] N. Lozare, Thermal Imaging Camera Credited for Saving Child. Firehouse.com News, 〈http://www.firehouse.com/news/99/10/19_camera.html〉, 1999.
[5] M.T. Richardson, Thermal triage, Fire Chief 45 (2001) 24–27.
[6] Firefighters Save A Life Fund, 〈http://www.fsalf.org/stories.htm〉, Modesto, CA.
[7] F.K. Amon, N.P. Bryner, A. Hamins, Thermal Imaging Research Needs for First Responders: Workshop Proceedings, NIST Special Publication 1040, National Institute of Standards and Technology, Gaithersburg, MD, 2005.
[8] ANSI/ISA 12.12.01-2000, Nonincendive Electrical Equipment for Use in Class 1 and II, Division 2 and Class III, Divisions 1 and 2 Hazardous (Classified) Locations, ANSI Publications, New York, NY, 2000.
[9] ASTM B 117-03, Standard Test Method for Salt Spray (Fog) Testing, ASTM International, West Conshohoken, PA, 2003.
[10] ASTM D 1003-00, Standard Test Method for Haze and Luminous Transmittance of Transparent Plastics, ASTM International, West Conshohoken, PA, 2000.
[11] ASTM D 6413-99, Standard Test Method for Flame Resistance of Textiles (Vertical Test), ASTM International, West Conshohoken, PA, 1999.
[12] ASTM F 1359-99a (2004), Standard Test Method for Liquid Penetration Resistance of Protective Clothing or Protective Ensembles Under a Shower Spray While on a Mannequin, ASTM International, West Conshohoken, PA, 2004.
[13] ASTM E 1213-97 (2002), Standard Test Method for Minimum Resolvable Temperature Difference for Thermal Imaging Systems, ASTM International, West Conshohoken, PA, 2002.
[14] ASTM E 1256-95 (2001), Standard Test Methods for Radiation Thermometers (Single Waveband Type), ASTM International, West Conshohoken, PA, 2001.
[15] ASTM E 1311-89 (2004), Standard Test Method for Minimum Detectable Temperature Difference for Thermal Imaging Systems, ASTM International, West Conshohoken, PA, 2004.
[16] ASTM E 1862-97 (2002), Standard Test Methods for Measuring and Compensating for Reflected Temperature Using Infrared Imaging Radiometers, ASTM International, West Conshohoken, PA, 2002.
[17] ASTM E 1933-99a (2005), Standard Test Methods for Measuring and Compensating for Emissivity Using Infrared Imaging Radiometers, ASTM International, West Conshohoken, PA, 2005.
[18] IEC 60529 Consol Ed. 2.1, Degrees of Protection Provided by Enclosures (IP Code),, International Standards Organization, Geneva, Switzerland, 2001.
[19] IEC 61000, Electromagnetic Compatibility (EMC), International Standards Organization, Geneva, Switzerland, 2005.
[20] IEC 61508-SER Ed. 1.0, Functional Safety of Electrical/Programmable Electronic Safety-Related Systems, International Standards Organization, Geneva, Switzerland, 2005.
[21] ISO 12233:2000, Photography—Electronic Still-Picture Cameras—Resolution Measurements, International Standards Organization, Geneva, Switzerland, 2000.
[22] MIL-STD 810F Method 513 Environmental Test Methods and Engineering Guidelines, Department of Defense Test Method

Standard for Environmental Engineering Considerations and Laboratory Tests, 2000.
[23] FPDM2 VESA-2001-6:, Flat Panel Display Measurement Standard, Video Electronics Standards Association, Milpitas, CA, 2001.
[24] NFPA 1221, Standard for the Installation, Maintenance, and Use of Emergency Services Communications Systems, 2007 Edition, National Fire Protection Association, Quincy, MA, 2007.
[25] NFPA 1971, Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting, 2007 Edition, National Fire Protection Association, Quincy, MA, 2007.
[26] NFPA 1977, Standard on Protective Clothing and Equipment for Wildland Fire Fighting, 2005 Edition, National Fire Protection Association, Quincy, MA, 2005.
[27] NFPA 1981, Standard on Open-Circuit Self-Contained Breathing Apparatus (SCBA) for Emergency Services, 2007 Edition, National Fire Protection Association, Quincy, MA, 2007.
[28] NFPA 1982, Standard on Personal Alert Safety Systems (PASS), 2007 Edition, National Fire Protection Association, Quincy, MA, 2007.
[29] M.K. Donnelly, W.D. Davis, J.R. Lawson, M.J. Selepak, Thermal environment for electronic equipment used by first responders, NIST Technical Note 1474, National Institute of Standards and Technology, Gaithersburg, MD, 2006.
[30] K. McGrattan, Verification and validation of selected fire models for nuclear power plant applications, Report NUREG-1824, US Nuclear Regulatory Commission, Washington, DC, 2006.
[31] A. Tewarson, Generation of heat and chemical compounds in fires, in: P.J. DiNenno (Ed.), The SFPE Handbook of Fire Protection Engineering, first ed., National Fire Protection Association and the Society of Fire Protection Engineers, Quincy, MA, 1988 (Section 1, Chapter 13).
[32] L.S. Rothman, D. Jacquemart, A. Barbe, D.C. Benner, M. Birk, L.R. Brown, M.R. Carleer, C. Chackerian, K. Chance, L.H. Coudert, V. Dana, V.M. Devi, J.M. Flaud, R.R. Gamache, A. Goldman, J.M. Hartmann, K.W. Jucks, A.G. Maki, J.Y. Mandin, S.T. Massie, J. Orphal, A. Perrin, C.P. Rinsland, M.A.H. Smith, J. Tennyson, R.N. Tolchenov, R.A. Toth, J. Vander Auwera, P. Varanasi, G. Wagner, The HITRAN 2004 molecular spectroscopic database, J. Quant. Spectrosc. Radiat. Transfer 96 (2005) 139–204.
[33] R.M. Silverstein, G.C. Bassler, T.C. Morrill, Spectrometric Identification of Organic Compounds, third ed., Wiley, New York, 1974.
[34] R. Siegel, J.R. Howell, Thermal Radiation Heat Transfer, fourth ed., Taylor and Francis, New York, NY, 2002.
[35] J.B. Fang, J.N. Breese, Fire development in residential basement rooms, Internal Report NBSIR 80-2120, National Bureau of Standards, Gaithersburg, MD, 1980.
[36] R.G. Gann, J.D. Averill, E.L. Johnsson, M.R. Nyden, R.D. Peacock, Smoke component yields from room-scale fire tests, NIST Technical Note 1453, National Institute of Standards and Technology, Gaithersburg, MD, 2003.
[37] A. Hamins, A. Maranghides, E. Johnsson, M. Donnelly, J. Yang, G. Mulholland, R. Anleitner, Report of experimental results for the international fire model benchmarking and validation exercise no. 3, NIST Special Publication 1013-1, National Institute of Standards and Technology, Gaithersburg, MD, 2005b.
[38] A. Hamins, A. Maranghides, K. McGrattan, E. Johnsson, T. Ohlemiller, M. Donnelly, J. Yang, G. Mulholland, K. Prasad, S. Kukuck, R. Anleitner, T. McAllister, Experiments and Modeling of Multiple Workstations Burning in a Compartment. Federal Building and Fire Safety Investigation of the World Trade Center Disaster. NIST Special Publication NCSTAR 1-5B,, National Institute of Standards and Technology, Gaithersburg, MD, 2005.
[39] R.D. Peacock, S. Davis, B.T. Lee, Experimental data set for the accuracy assessment of room fire models, Report NBSIR 88-3752, National Bureau of Standards, Gaithersburg, MD, 1988.
[40] W.M. Pitts, E.L. Johnsson, N.P. Bryner, Carbon monoxide formation in fires by high-temperature anaerobic wood pyrolysis, Proc. Combust. Inst. 25 (1994) 69–70.