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Detecting Hidden Fires On Aircraft Using Thermal Imaging Cameras

Authors: Ron Gould, Simon Hind, Kitsy Sorensen, (Frontier Airlines), Francois Jacquet (OIAA)

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EXECUTIVE SUMMARY

This project, funded by the National Research Council (NRC) Working and Travelling on Aircraft (WTA) program, included a series of tests focussed on the safety problem of detecting and locating hidden fires on commercial aircraft. Current training instructs aircraft cabin crews to attempt to find the location of hidden fires, say behind a fuselage liner or in an overhead bin, by using the back of their hand to feel for a hot spot. This process is likely problematic being inaccurate and slow during a fire event when rapid, accurate response is required and limited quantities of firefighting agent are available. The project objective was to demonstrate the use of low cost, hand-held thermal cameras for this hidden fire detection task, which could increase overall safety by allowing cabin crews to quickly locate hidden fires with higher levels of accuracy.

TABLE OF CONTENTS

EXECUTIVE SUMMARY ..... **V**
TABLE OF CONTENTS ..... **VII**
LIST OF TABLES ..... **X**
ABBREVIATIONS ..... **XI**
SYMBOLS ..... **XI**
1.0 INTRODUCTION **1**
2.0 CURRENT CABIN CREW FIREFIGHTING TRAINING **2**
3.0 THERMAL CAMERAS **5**
3.1 SEEK COMPACT 5
3.2 FLIR C2 5
3.3 FLIR T650SC 5
3.4 TIC DISPLAY CAPABILITIES 6
4.0 BASELINE THERMAL OF CABIN INTERIOR **9**
5.0 HEAT SIMULATION **9**
5.1 TEST SITES 10
5.2 SMOKE SIMULATION WITH FOG 13
6.0 CHALLENGES USING THERMAL CAMERAS **16**
6.1 EMISSIVITY, REFLECTIONS AND SOLAR HEATING 16
6.1.1 Emissivity *16*
6.1.2 Thermal reflection *17*
6.1.3 Solar Heating *18*
7.0 B737-200 THERMAL CAMERA TESTS **19**
7.1 SITE P1 – OVER-HEAD LUGGAGE BIN 19
7.2 SITE P2 – OVER-HEAD LUGGAGE BIN 21
7.3 SITE P3 – PASSENGER SEAT 23
7.4 SITE S1 – OVER-HEAD LUGGAGE BIN 27
7.5 SITE S2 – OVER-HEAD LUGGAGE BIN 28
7.6 SITE S3 – CEILING PANEL 30
7.7 SITE S4 – PASSENGER SEAT-BACK DISPLAY 31
7.8 SITE G1 – GALLEY COFFEE HEATER 33
7.9 HEATED AIR – OVER-HEAD LUGGAGE BIN 36
7.10 POWERED CABIN – IN-FLIGHT 40
7.11 DETECTION FROM A DISTANCE 42
8.0 THERMAL CAMERA APPLICATIONS **43**
9.0 OTHER POTENTIAL USES OF THERMAL CAMERAS **43**
10.0 SUGGESTED MINIMUM DEVICE REQUIREMENTS **45**
11.0 CONCLUSIONS **46**

12.0 ACKNOWLEDGEMENTS 47

13.0 REFERENCES 48

APPENDIX A : THERMAL IMAGING CAMERA SPECIFICATIONS A1

LIST OF FIGURES

Fig. 1. OIAA ERS Trainer: Passenger B737-200. 1
Fig. 2. Greyscale and colour thermal images. 7
Fig. 3. Colour and greyscale thermal images. 7
Fig. 4. SEEK Thermal image of TIC operator, 20ºC threshold. 8
Fig. 5. Electric heater strip installation. 9
Fig. 6. Electric heater strip on metal plate. 10
Fig. 7. B737-200 single class cabin layout. 11
Fig. 8. Cabin cross-section, looking aft with dimensions and test sites. 12
Fig. 9. Fog generator on floor in aft galley. 14
Fig. 10. FLIR T650sc visual and thermal image pair of heat source in ceiling panel. Note second firefighter obscured by fog. 14
Fig. 11. SEEK Thermal and Visual image pair of port OWE area, in fog. 15
Fig. 12. FLIR T650sc Visual and Thermal image pair, in fog. 15
Fig. 13. SEEK visual and thermal pair of the ERS aircraft exterior at the L1 door. 17
Fig. 14. FLIR T650sc thermal reflection. 17
Fig. 15. FLIR T650sc solar heating visual and thermal image pair. Mechanical shades open and closed (X). 18
Fig. 16. P1 heater and TC installation in port Bin 18. 19
Fig. 17. SEEK Visual and Thermal image pair of Bin 18. 19
Fig. 18. FLIR T650sc visible and thermal image pair of Bin 18. Greyscale with threshold false-coloured. 20
Fig. 19. SEEK Compact visible and thermal image pair of Bin 18 in fog. 20
Fig. 20. Close-up views of Bin 18, site P1. 21
Fig. 21. Site P2 heater and TC installation in port Bin 9. 22
Fig. 22. Site P2 Visual and Thermal image pairs, from forward, in partial fog. 22
Fig. 23. Visual and Thermal image pair, from aft. Sites P2 and S3 marked. 22
Fig. 24. Views of seat set with heater strip installed. 23
Fig. 25. SEEK thermal views of a seat occupied and recently vacated. 23
Fig. 26. Views of back side of seat set, site P3. 24
Fig. 27. Thermal views of seat back lower valence, site P3. 25
Fig. 28. SEEK and FLIR T650sc views of heater at rear of bottom cushion, site P3. 26
Fig. 29. Visual and Thermal views of heater between seat cushions, site P3. 26
Fig. 30. One lighted candle in bottom of port Bin 19, site S1. 27
Fig. 31. Visual and Thermal views of heating event in starboard Bin 17, site S2. 29
Fig. 32. Site S3 Heater installation and SEEK Thermal views. 30
Fig. 33. Visual and Thermal image pairs of ceiling panel, site S3. 31
Fig. 34. Seat-back display with electric heater strip energized, site 4. 32
Fig. 35. Visual and Thermal views of operational seat-back displays. 32
Fig. 36. Aft cabin galley area viewed from cabin, site G1. 33
Fig. 37. Aisle side view and coffee maker bays of aft starboard galley, site G1. 33
Fig. 38. Heat lamp effect on bottom partition of upper coffee maker bay, site G1. 34
Fig. 39. View of heated galley aisle-side wall, site G1. 34
Fig. 40. SEEK Visual and Thermal image pair of coffee maker bay, in fog, site G1. 35
Fig. 41. Single coffee heater carafe in upper galley bay, site G1. 35
Fig. 42. SEEK Visual and Thermal views of powered coffee heater, site G1. 36
Fig. 43. Two-bin over-head luggage bin. 37
Fig. 44. Single bin with two doors and half-height internal divider. 38
Fig. 45. Cabin ceiling panel mock-up and in-flight. 39

Fig. 46. PED power transformer. 40
Fig. 47. Aircraft cabin ceiling fluorescent fixtures. 41
Fig. 48. SEEK Thermal view of energized lavatory water heater. 41
Fig. 49. Electric heater strip test sites viewed from a distance. 42
Fig. 50. Potential to detect leaking aircraft door seal in-flight. 44
Fig. 51. SEEK Thermal views of windshields in two aircraft cockpits. 44
Fig. 52. SEEK Thermal and visual views. Centre Instrument Panel and Control Pedestal. 45

LIST OF TABLES

Table 1. Test sites. 12

ABBREVIATIONS

AAIB	Air Accidents Investigation Branch (UK)
AC	Advisory Circular
BS	Body Station
Combi	Cabin main deck configured for both cargo and passengers
cm	Centimeter
ECS	Environmental Control System
ERS	Emergency Rescue Services
FAA	Federal Aviation Administration
ft	Feet
FOV	Field of view
Hz	Hertz. Unit of frequency: cycles per second
IR	Infrared
LCD	Liquid Crystal Display
LTR	Laboratory Technical Report
m	Meter
OIAA	Ottawa International Airport Authority
OWE	Over-Wing Exit
NRC	National Research Council Canada
PBE	Personal Breathing Equipment
PED	Personal Electronic Device, Portable Electronic Devices
PPE	Personal Protective Equipment
PORT	Left side of aircraft, looking forward
SCBA	Self-Contained Breathing Apparatus
STBD	Starboard. Right side of aircraft looking forward
TC	Thermocouple
TIC	Thermal Imaging Camera
µm	Micrometre (Micron). Unit of measurement for wavelengths of infrared radiation
WTA	Working and Travelling on Aircraft

SYMBOLS

ε	Emissivity: ratio. Effectiveness of a surface to emit energy as thermal radiation
$\tilde{v}$	Volts, alternating current
°C	Degrees Centigrade
°F	Degrees Fahrenheit

1.0 INTRODUCTION

Airport fire and runway clearing vehicles are often equipped with infrared (IR) cameras. These thermal imaging cameras (TIC) were intended as driver's aids and, in the case of the fire services, specifically to assist the operator in navigating to the scene of an incident in darkness or inclement weather. In-house research by the Ottawa International Airport Authority (OIAA) Emergency Rescue Services (ERS) has changed that to where the TIC have been used in training and live fires to detect aircraft substructure, aid in fuselage piercing, locate the seat of the fire, observe normal aircraft and engine exterior heat signatures and to solve problems with exterior apparatus in low temperatures [1]. These ruggedized, remote-controlled, pan and tilt camera modules with internal display and record features are expensive. The recent advent of low cost TICs aimed at the hunting, construction and handyman consumer has allowed safety equipment suppliers to offer first responders with hand-carried TICs or units mounted on helmets and even inside self-contained breathing apparatus (SCBA) face masks.

As of June 2017 the Federal Aviation Administration (FAA) reported 18 incidences of lithium battery fires onboard aircraft and in airports. In 2016 there were 31, with 16 in 2015, and nine in 2014 [2]. This is not to ignore the separate and recurring incidences of overheating and smoke from installed systems in the cabin and cockpit. Flight attendants are the first responders in the closed aircraft environment where fire poses a most serious threat, which they must address with finite time and resources. What tools do they have to prevent a catastrophic result especially when both the aircraft and the passengers are operating with much increased electrical and chemical ignition and fuel load potential? Personal electronic devices (PED), digital flight bags, entertainment systems and the move towards electric flight control aircraft are balanced against a few crew, a few extinguishers, possibly smoke hoods and no tools but their hands and what utensils may be found in the galley to defeat an on-board in-flight fire. This is no longer the threat of a lit match or a smouldering cigarette.

The project was executed in collaboration with the OIAA ERS. The majority of tests were performed on the OIAA ERS's Boeing 737-200 training aircraft, shown in Fig. 1. The aircraft is configured with a passenger interior.

Fig. 1. OIAA ERS Trainer: Passenger B737-200.

The B737 training aircraft was donated to the ERS in an incomplete passenger configuration. Some ceiling and over-head baggage bins were missing, as were many seat sets. The final operating configuration had been as a Combi, where the forward section was fitted for bulk main-deck cargo. The interior has since been populated with additional seat sets, but they do not fully fill the cabin at the normal density (99 seats). The aircraft electrical systems can not be powered.

First, the decommissioned aircraft was surveyed to establish baseline thermal imaging data. Next, flameless heat sources (conductive heater elements) were used to generate controlled hot spots of known temperature on the backside of various structures to investigate the feasibility of using hand held thermal cameras to find and quantify the heat sources. One test was conducted using the heat from a quartz halogen lamp, one with a hot-air gun and another employed the flame of a single candle. In-flight visual and thermal images were collected by the authors during personal commercial flights. The areas investigated were over-head luggage bins, cabin seats (cushions and seat-back displays) and galley areas. The lavatories were not included in this study because commercial aircraft have installed fire detection and suppression systems in these areas. Power distribution panels in the galleys and cockpit were not investigated but would be of interest (circuit-breakers and cooling fans). The aircraft was single-class and therefore walled individual passenger pods with power points, entertainment displays and powered reclining seats are not represented in this study although they would be of interest for a follow-on investigation.

The project started with the SEEK Compact smartphone thermal camera attachment ($300) as well as a FLIR 650sc unit owned by NRC Construction ($36,500). The project purchased a FLIR C2 ($750) to evaluate the benefits and limitations of a wider range of thermal imaging cameras for the on-aircraft fire detection application. There are now a variety of thermal imaging cameras being suggested for use by firefighters which can be purchased for less than $1,000.

2.0 CURRENT CABIN CREW FIREFIGHTING TRAINING

Cabin crews are trained to find and aggressively fight hidden fires in the cabin. Hidden fires are those that are not visible or easily accessible. Indications of a hidden fire may be a hot surface, smoke, fumes, unusual odours and snapping or popping noises. Other indications of a hidden fire could be exhibited by passengers or crewmembers displaying symptoms of eye irritation, sore throats, coughing, or headaches. Such symptoms can be an indication of fumes before smoke or a fire is visible.

If flames are not visible, inflight crew must quickly find the source of the fire. This is done by various methods and tools, varying between types of aircraft, locations of hidden fires, and airline company procedures. Though equipment may vary between airlines and aircraft, all have hand fire extinguishers onboard. Halon is a commonly used extinguisher agent. Training indicates that the crews may use Halon on Class A, B, and C fires. Additionally water extinguishers may be available. Water extinguishers are used only on Class A fires and must be used on a Class A fire, even if Halon was initially used.

Protective breathing equipment (PBE) or smoke hoods, to protect from smoke and toxic fumes, are required to be placed within three feet of every installed fire extinguisher. Inflight crews are trained to first don a PBE before fighting a fire. A PBE is designed to provide breathing oxygen for approximately 15 minutes.

An insulated crash axe may be available to some flight crews. Most crash axes are placed in a "safe" place, away from public access. The crash axe may be used to pry open a panel or to poke a hole in a panel so that a Halon extinguisher nozzle could be inserted.

Fire gloves may be available to cabin crews. Accessibility of various equipment to cabin crews varies between airlines.

Non-standard resources and equipment can be re-purposed to fight fires. Improvisational use of oven mitts as fire gloves, non-alcoholic beverages as extinguishing agent, waste bins as containers to immerse PEDs, and seat cushions to smother flames, are examples of additional resources.

The most obvious, readily available method trained to detect a hot surface is the "back of the crewmember's hand". Inflight crew are instructed that the palm of the hand has thicker skin and is not as sensitive to temperature changes. Additionally, if a crewmember were to burn the palm-side of the hand, it could impede or complicate firefighting activities or operating an emergency exit door and conducted a passenger evacuation. This procedure is backed by Advisory Circular (AC)120-80A, dated 12/22/14, "What is the Best Way to Locate Hot Spots on a Door or Interior Panel Before Attempting to Open or Remove it?."

Once a hot spot has been discovered, it will be necessary to get to the base of the fire before using any extinguishing agent. This may be done by removing panels or making an incision large enough to insert the nozzle of an extinguisher. Crews are trained to use a crash axe if available and accessible. If not, improvised tools range from ice tongs, spoons, scissors to knitting needles or a high heel, just to name a few.

Inflight crewmembers have been trained on basic fire chemistry and know the importance of removing heat, fuel, or oxygen. This is typically accomplished with a fire extinguisher. Crewmembers identify the suspected class of fire and obtain the correct type of extinguisher onboard. An example would be an electrical wiring fire, which is Class C. Crewmembers would use a Halon extinguisher rather than a water extinguisher, aqueous-based extinguishing agent, or non-flammable liquid.

Crew coordination and communication are essential in the event of an inflight fire. The firefighting effort requires all crew members to know their duties, follow their training, know which equipment to use, how to use it, and where it may be found. These duties of cabin crew can be divided into three main roles: the firefighter, the communicator, and the assistant firefighter. All other crewmembers play a supporting role.

The crewmember that finds the fire is the firefighter. The responsibility of the firefighter is to notify other cabin crewmembers, get the nearest appropriate fire extinguisher, don a PBE, and fight the fire aggressively.

The second crewmember will be the communicator informing all other crewmembers of the location of the fire. Communication should include: severity of the fire, density of the smoke, color and odour of the smoke, type of extinguishers used, number of extinguishers used, progress of the firefighting, and containment of the fire. Clear, precise, and timely communication is a key factor in survival.

Training indicates that a detected fire will have the flight deck crew donning their oxygen masks and initiating a descent to 10,000 feet. Cabin recirculation fans may be turned off to inhibit the circulation of smoke, combustion gases and Halon vapours. Communication may be difficult due to the PBE smoke hoods and flight deck oxygen masks. If the fire is of an electrical nature, power to that affected area may be cut off or individual circuit breakers could be pulled.

The third crewmember will be the assistant firefighter, donning a PBE and retrieving additional firefighting supplies. This assistant may replace the first firefighter or come alongside to assist. Removing flammable material from the area is one way of assisting.

The role of the other crewmembers is that of support and surveillance. Passengers may need to be moved to another location in the cabin, receive first aid, or be reassured. Passengers could be instructed to cover their noses and mouths and to breathe through their clothing. Portable oxygen bottles need to be moved away from the location of the fire. If the source of the fire seems uncertain, surveillance is extremely important, especially if it is suspected that a passenger may have intentionally started the fire.

Monitoring the affected area is trained as well. Cabin crewmembers are to be vigilant in visually monitoring the area due to the fact that there is no other way to ascertain that the fire is entirely out, that nothing is heating up again or burning elsewhere.

3.0 THERMAL CAMERAS

The three IR cameras employed are sensitive in the 7.5 to 14 microns spectral range and have a colour-capable displays with the option to display in greyscale. All can record still images with temperature values overlaid. See Appendix A for the technical specifications for these cameras.

3.1 SEEK COMPACT

This TIC has a 206 x 156 pixel sensor with a temperature sensitivity of -40°F to 626°F (-40°C to 330°C). The sensor refresh or frame rate is 9 Hz. The emissivity setting is not adjustable. (Emissivity is the effectiveness of a surface of a material to emit energy as thermal radiation.)

The TIC module is attached to and powered through a port on the perimeter of either an Apple or an Android smart phone or other compatible PED. Therefore the displayed output image is dependent on the screen size of the host device. Visual camera specifications are also determined by the host PED. In this case the host device was an iPhone 5c with a 4-inch diagonal display (640 x 1136 pixels).

The SEEK thermal camera attaches to the bottom of the iPhone while the phone's visual camera is at the top. Also, the field-of-view of the two cameras are not the same. Therefore the temperature tags in the visual camera images are displaced especially in close-up situations. The user must refer to the thermal image for proper placement. Both images are captured at the same time. The operator, scanning for hidden fires, will only see the thermal image displayed.

3.2 FLIR C2

The FLIR C2 has a 80 × 60 pixel sensor with a temperature range between 14°F to 302°F (–0°C to +150°C). The sensor refresh rate is 9 Hz. The colour display is 3" diagonal, (320 x 240 pixel). Emissivity can be selected or customized. The thermal and visual cameras are mounted side-by-side.

3.3 FLIR T650SC

This is a sophisticated high-end visual camera combined with a larger 640 × 480 pixel IR sensor that has a temperature sensitivity between -40°F and 1202°F (-40°C to 650°C) and a frame refresh rate of 30 Hz and a 4.3 inch Liquid Crystal Display (LCD) (1024 × 600). Threshold: above, below and interval. Emissivity correction can be varied from 0.01 to 1.0.

3.4 TIC DISPLAY CAPABILITIES

The three cameras cover a wide range of sensors thus providing an opportunity to observe their spectral response. At any distance the number of elements within the temperature measurement area will affect the sensitivity to and accuracy of the measure.

All three cameras offer Centre Spot and Hi/Low temperature display as well as Threshold false-colour modes.

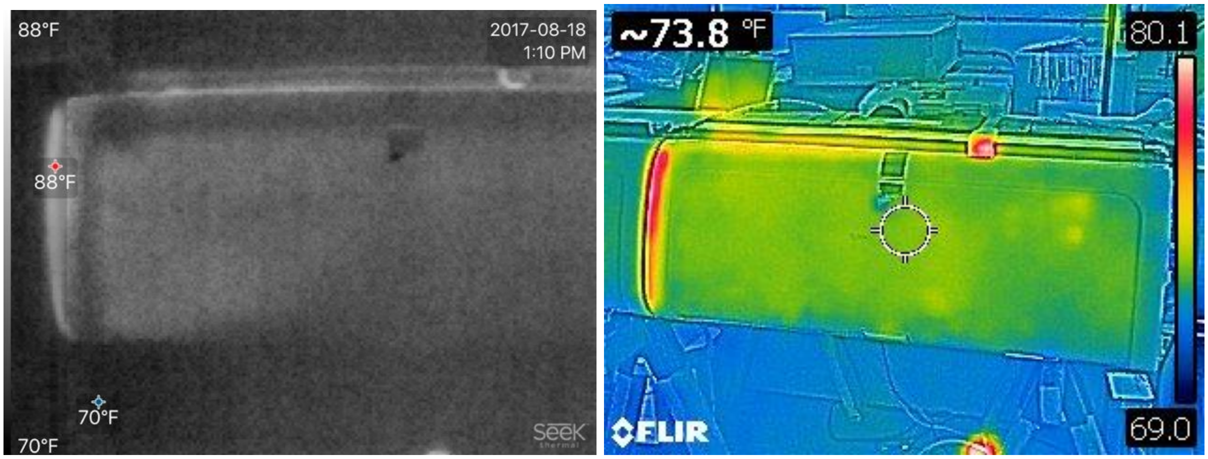
The FLIR C2 and T650sc employ image data from both onboard camera sensors in a live composite image termed “Thermal Fusion” that overlays the visual edges of objects onto the thermal image. This assists in outlining what is in view when the various objects/surfaces are nominally at the same temperature. This feature requires processing power and the display pauses between updates. The presence of smoke would deteriorate this visual aid.

Displaying temperature values as a greyscale image provides an intensity map of the surface. The preference has been to set the thermal camera displays to greyscale with “White is HOT” as the pallet. All of the cameras also offer Black is Hot and various false-coloured pallets. These coloured pallets are devised to increase contrast to ease the recognition of hot spots, but their application is based solely on operator preference. The colours have no direct correlation to a fixed temperature and thus vary with the minimum and maximum values in the view.

A threshold temperature can be set in the camera software such that temperatures above a preset value are colourized in the displayed image. This feature, if set above known peak operating temperatures of installed systems, would provide for a visual warning of overheat or fire. A specific threshold temperature has not been set yet. This can only be determined following an assessment in an operational aircraft.

Fig. 2a shows a greyscale SEEK Compact thermal image of an overhead luggage bin. The highest and lowest temperatures are displayed both on the left edge and by two targets: red indicating the location and temperature of the hottest spot, and blue the value and location of the coldest spot. This setting will be referred to as “Hi/Lo”.

Fig. 2b shows a FLIR C2 image of the same subject. The scene is false coloured. On the right side the maximum and minimum temperatures in the scene are displayed. In the top left corner the camera is displaying the temperature inside the centre reticule. This setting will be referred to as “Centre Spot”.

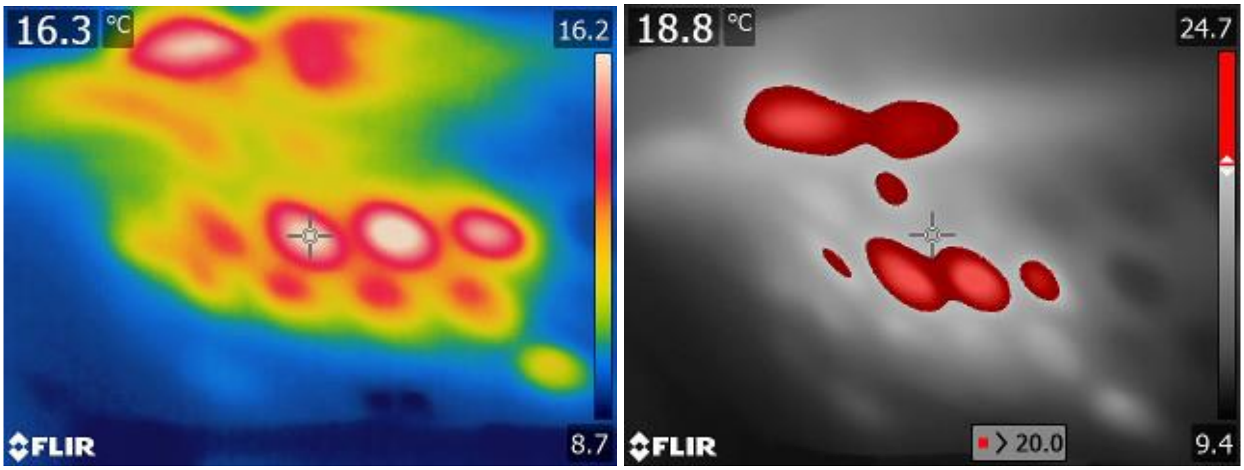


a) SEEK Thermal b) FLIR C2

Fig. 2. Greyscale and colour thermal images.

A temperature threshold has not been set on either camera. The FLIR C2 has co-axial visual and thermal cameras and their images have been merged such that hard edges detected in the visual scene are superimposed on the thermal image, as shown in Fig. 2b. The manufacturer terms this "Thermal Fusion". When an area is nominally at a similar temperature, this processing aids in identifying objects that would otherwise not be apparent in the thermal scene. Smoke would negate this function as the visual scene becomes obscured.

Fig. 3a is false-colour with no threshold set, while Fig. 3b shows the areas that exceed a 20ºC threshold setting in shades of red. These two views compare the same area taken with the FLIR T650sc.



a) FLIR T650sc. No threshold set b) FLIR T650sc. 20ºC threshold set

Fig. 3. Colour and greyscale thermal images.

A SEEK Compact thermal image of a person in the test aircraft cabin is shown in Fig. 4. The camera is set to “White is Hot”, centre spot, with a threshold of 20ºC. Note that the increasing temperatures are represented in a gradient starting from black up to white at the threshold. Above the threshold the areas are false-coloured starting with yellow, then red and the highest temperatures are again black.

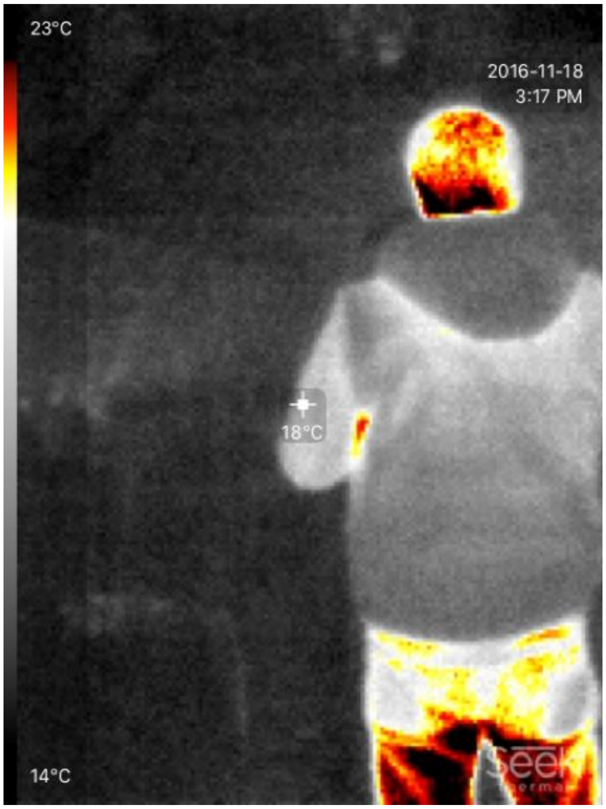


Fig. 4. SEEK Thermal image of TIC operator, 20ºC threshold.

4.0 BASELINE THERMAL OF CABIN INTERIOR

The interior of the un-powered aircraft was surveyed using the SEEK thermal camera to evaluate the various painted, coated plastic and metallic surfaces for problematic responses that might introduce false calls when evaluating thermal responses. It was expected that metal surfaces would radiate very differently or reflect heat sources, such as the body of the operator. At the default emissivity setting of the cameras, with most non-metallic materials radiating efficiently, the reported temperatures will be fairly accurate, while metallic surfaces would have to be compensated for to achieve accuracy. Fortunately the intended application of a thermal camera to rapidly locate hidden abnormal heat sources is not so much a question of accurate temperature measurement than it is to allow a direct comparison to adjacent identical structure. In the following tests there were no occurrences where metallic surfaces confused the analysis by radiating at a higher perceived temperature than the installed heat source.

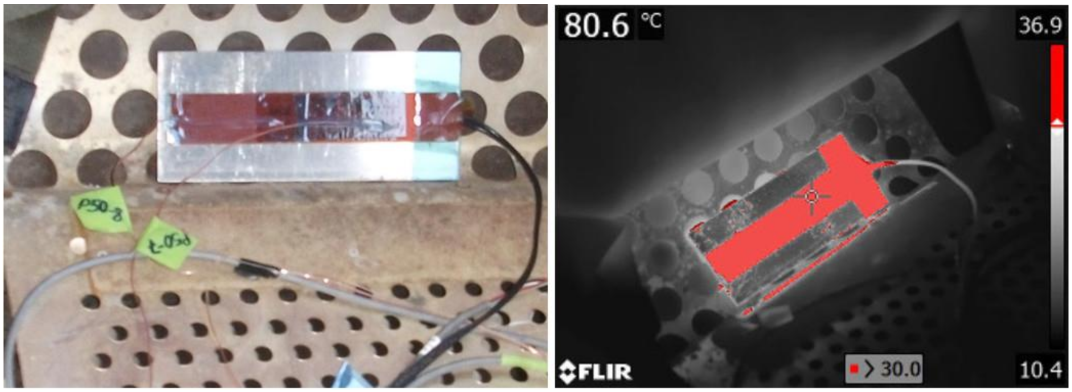
5.0 HEAT SIMULATION

The investigation included real thermal loads using electric heater strips, a quartz halogen lamp, a hot-air gun and the open flame of a single candle.

a) Computer and heater control in aft galley b) Heater installation in bins, seats, attic

Fig. 5. Electric heater strip installation.

A computer in the aft galley, shown in Fig. 5a, controlled the heater strip power supplies individually via a thermocouple (TC) attached to each heater. A heating ramp rate was set along with a maximum temperature to be maintained (104ºF or 194ºF, 40ºC or 90ºC). The flexible wire-grid heater strips were 6 x 1 inch (15.2 x 2.5 cm) and affixed to a small aluminium plate. At each heater installation, a second thermocouple was mounted on the structure to monitor and record the local heating, as shown in Fig. 6. The ambient temperature in the un-powered, unheated aircraft at the times of the tests varied between -4ºF to 57ºF (-21ºC to 14ºC). Very low maximum heater temperatures were set to avoid heat damage and unintentional fires. The highest temperature measured in a 40ºC test was 38ºC, and in a 90ºC test was 88ºC.



a) Control TC on heater strip. Monitor TC hidden. b) Thermal view of energized heater.

Fig. 6. Electric heater strip on metal plate.

5.1 TEST SITES

The ERS B737-200 passenger cabin is 62.125 feet (18.9 m) long from the cockpit bulkhead body station (BS) 259.5 to the aft pressure dome (BS1040). The passenger compartment is 54.8 ft (16.7 m) long, as shown in Fig. 7. The interior panels and cabinetry are 1980s vintage. The over-head bin numbering system, as marked in the cabin, is also illustrated.

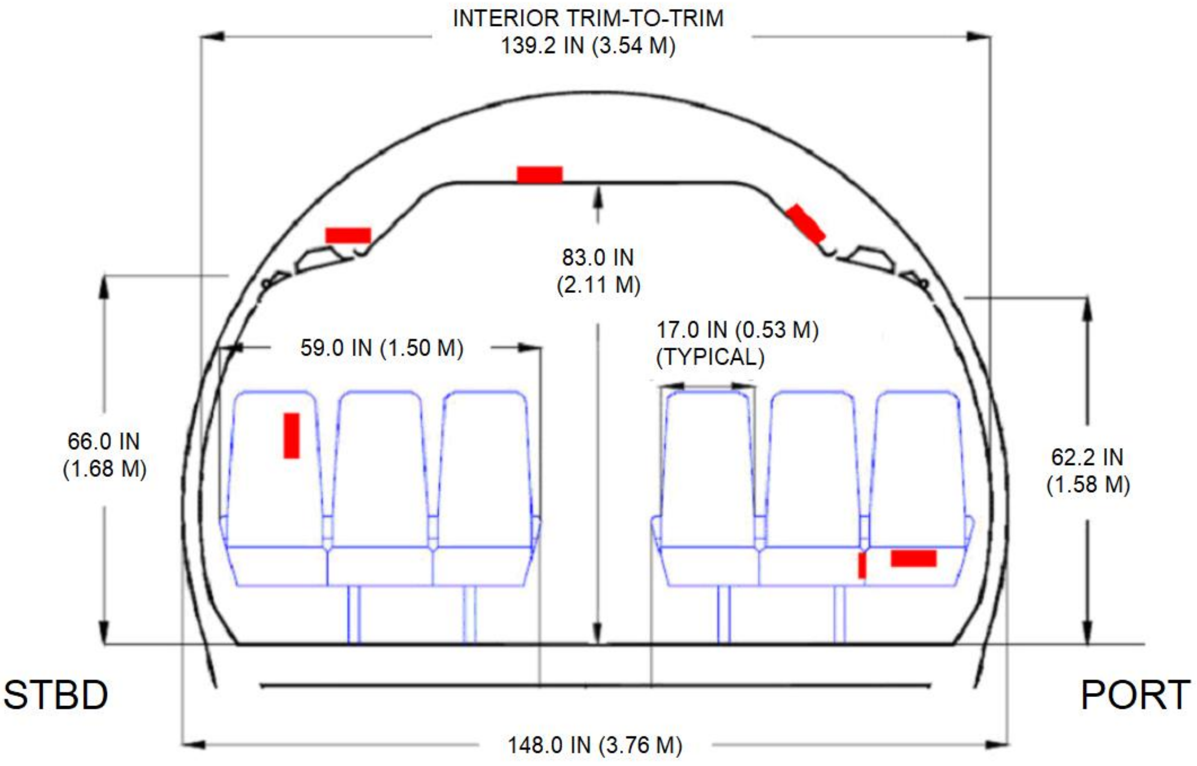


Fig. 8 shows the cabin in cross-section. Table 1 provides a description of the eight test sites.

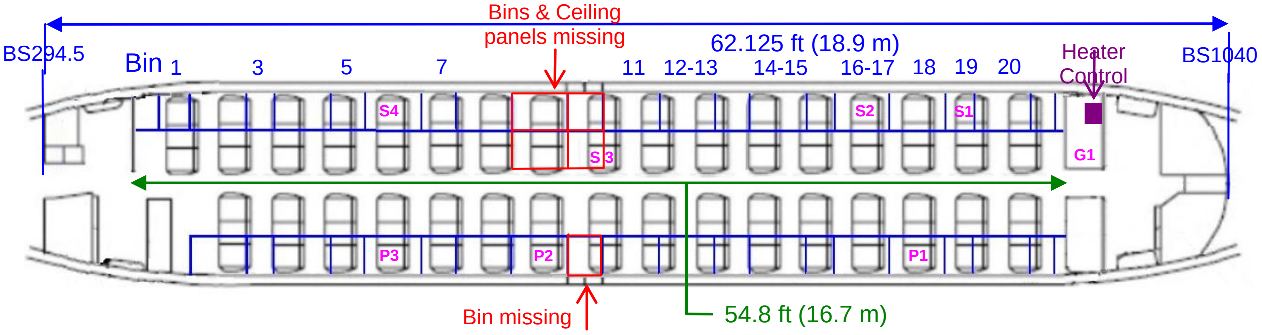


Fig. 7. B737-200 single class cabin layout.

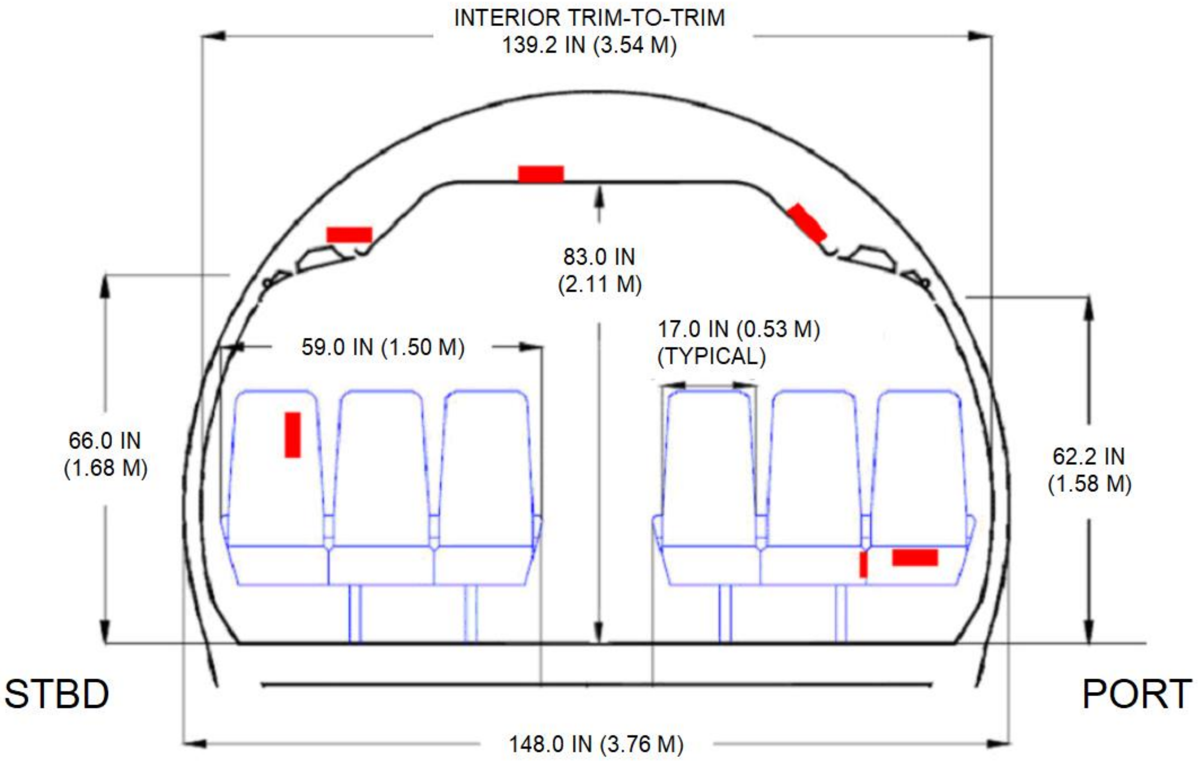


Fig. 8. Cabin cross-section, looking aft with dimensions and test sites.

SITE	Location	Description
P1	Bin 18	Bin door, top edge, centre. On inner metal edge, above latch.
P2	Bin 9	Bin door, inside surface, aft of centre, half height.
P3	Seat 5A	Seat-set, under and between seat cushions.
S1	Bin 19	Candle in metal pan. Bottom centre of bin.
S2	Bin 17	Inside bin on aft sidewall.
S3	Bin 11	Ceiling panel, top surface, aft edge.
S4	Seat 5F	Seat-set, seatback display, under bezel, inboard side.
G1	Aft Galley	Heat lamp. Upper coffee heater bay.

Table 1. Test sites.

Sites S1, S2, P2 and P3 are significant because these luggage bins may contain a heat source (damaged or shorted PED battery that produces heat and open flames) combined with an adjacent fuel supply (baggage container and contents potentially including other battery cells). Initially they may be the source of an early warning odour and/or smoke. The heat source cannot be remotely turned off.

Site S3 represents a situation where an electrical arc in the aircraft's wiring ignites the covering of the adjacent fuselage insulation batt which, despite certification tests for flammability and self-extinguishment, could be a fuel [3]. A recent cabin wall wiring short circuit behind a cabin liner panel that is not easily accessed or removed is a relevant example [4]. The electrical power source can be turned off.

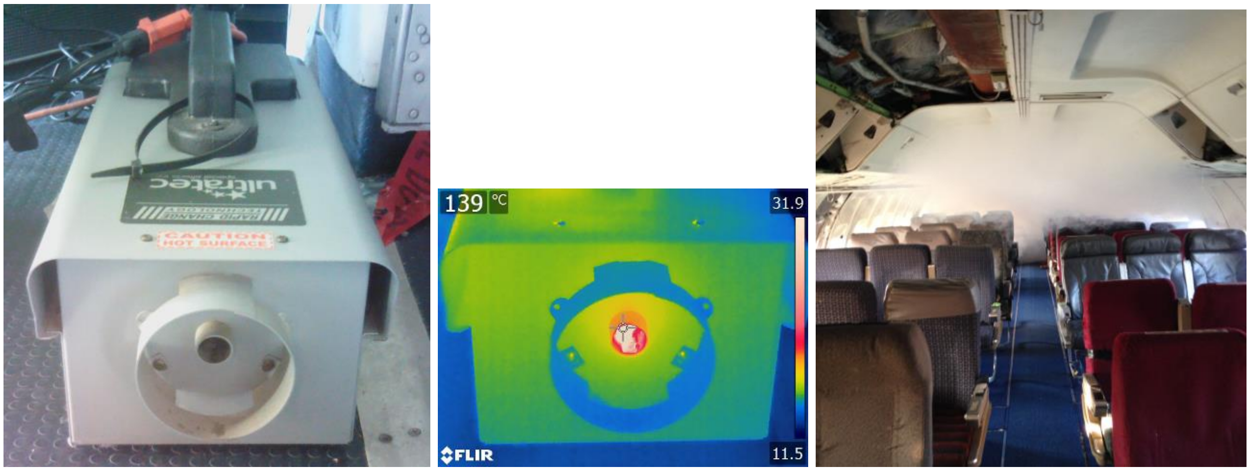
Site S3 addresses the increasing population of installed, aircraft-powered, electronic devices in the cabin (displays, power points). These locations and ignition sources do not have access to fuel sources much beyond their components and these respond to arcing and overheating with melting and a burning odour. The electrical power can be turned off.

Site P3 simulates an event where a PED is damaged when crushed by the seat occupant or seat mechanism [5]. The potential for fire is limited to the stored chemical and electrical energy of the device and ignition of the device body. The adjacent aircraft structures (seat coverings and padding) are certified for flammability but remain a source of smoke and fumes. The heat source can not be turned off. Damage to PEDs by being crushed in the mechanisms of reclining seats could not be directly simulated.

Site G1 represents a source of overheating, odour and smoke. Flight diversions for fires in ovens are not uncommon; events involving the ovens [6] and coffee makers [7] themselves do occur. The electrical power to these devices can be turned off. This scenario is intended to determine if such over-heat events could be identified through the adjacent sandwich-construction cabinetry walls. This will become more important now that both business and first-class seating with electronic displays and power points is being arranged in walled pods that make searching for hidden fires more laborious.

5.2 SMOKE SIMULATION WITH FOG

Employing a theatrical fog generator, the project trialed the thermal cameras under simulated smoke conditions. This not only tested the camera's capability to "see" through smoke and assess the impact on locating heat sources, but also assessed the operator's ability to view the camera display screen and operate the unit effectively while wearing the appropriate PPE. The simulated smoke was generated by pumping a commercially prepared glycol/water mix into a heating device, where it is vaporized, shown in Fig. 9a and b. Mixing with the cooler cabin air causes droplets to condense, creating an opaque fog. The fog can be sufficient to obscure both the operator's and the visual camera view.



a) Fog generator b) Thermal view of generator c) Smoke filling cabin

Fig. 9. Fog generator on floor in aft galley.

The fog generator was positioned on the floor in the aft galley. The adjacent R2 cabin door was open slightly to allow for power cables from the gasoline-powered 110ṽ generator on the ground outside the aircraft. The starboard over-wing exit (OWE) was removed to allow entry and exit of participants off the wing.

The fog became thick enough that eventually personnel could not navigate the interior of the aircraft without the aid of a thermal camera. The participants, even those firefighters wearing SCBA with full-face mask could still manage to see the thermal camera displays through a face shield or respirator mask, as shown in Fig. 10. Note the heat source in the ceiling panel and the second firefighter, who cannot be seen in the optical image.

Fig. 10. FLIR T650sc visual and thermal image pair of heat source in ceiling panel. Note second firefighter obscured by fog.

Fig. 11 shows SEEK Compact visual and thermal camera views captured of the port OWE area after the cabin was filled with fog.

Fig. 11. SEEK Thermal and Visual image pair of port OWE area, in fog.

Fig. 12 shows a firefighter using the SEEK Compact to detect a heat source in an overhead bin while visibility is impaired by fog.

Fig. 12. FLIR T650sc Visual and Thermal image pair, in fog.

Simulating smoke with an opaque fog does not answer whether a real fire with a heavy airborne particulate content would obscure the thermal camera view sufficiently to impair or prevent the detection of a heat source. This problem has been recently encountered, though well after the fire had been established [8]. In the initial stages, where an odour, visible smoke or an elevated temperature alarm has prompted a search, the airborne particulate in the smoke may not have reached a problematic density.

6.0 CHALLENGES USING THERMAL CAMERAS

The research to date has involved heating techniques and scenarios that centred on the heat transfer through various materials and structures, the surfaces of which radiate to the thermal detector array. These were not fully representative of hidden fires occurring in an operational cabin environment.

A choice of emissivity settings is not deemed necessary in that accurate temperature measurement is not paramount. Judging by the materials and surface finishes encountered in cabin interiors to date, the typical default setting ($\varepsilon > 0.9$ to < 0.98) would be suitable. In long and narrow aircraft cabins, where rapid initial searching is confined to moving along the aisle, the viewing angle between the radiating surface and the TIC detector plane will adversely affect the validity of the displayed temperature until the angle is less than 60 degrees to normal.

The three cameras all have sufficient spatial resolution (heat detecting elements in their array) to produce valid temperature readings over the relatively short distance of the cabin length. Of more concern is the narrow width of the cabin, as the detectors are angularly dependant. The viewing angle is important if a measurement is to be accurate enough to be used as a threshold alarm.

6.1 EMISSIVITY, REFLECTIONS AND SOLAR HEATING

Three physical phenomenon which cause challenges when using TIC cameras for the detection of hidden fires in aircraft cabins are described in the following sections.

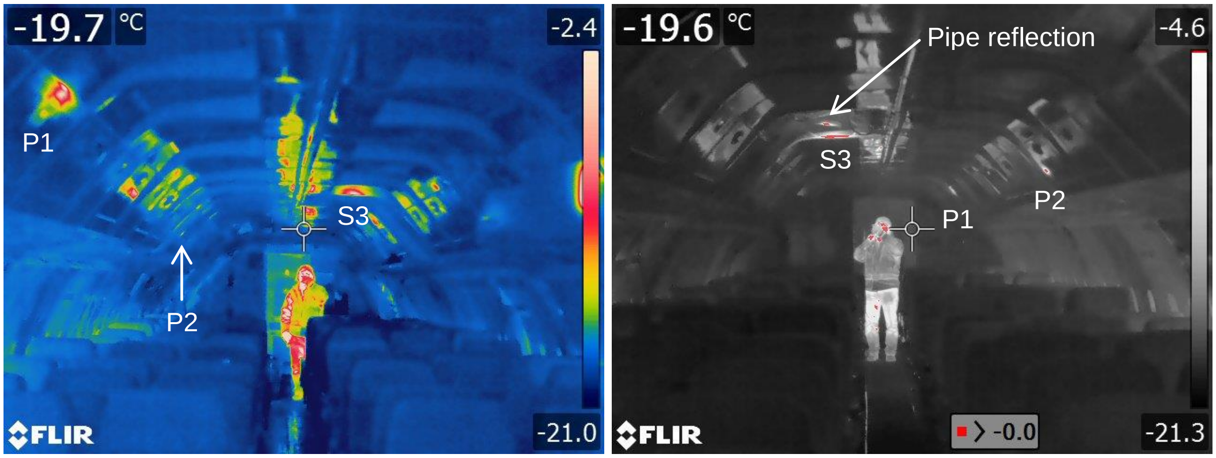
6.1.1 EMISSIVITY

Prior to this project, the work with thermal imaging and analysis has been directed to the exterior of the aircraft. Examples of surfaces and materials that have differing emissivity ratios and how they affect the image and the temperature reported are shown in Fig. 13 where the pallet is “White is Hot”. The different emissivity of the unpainted metal door handle, sill plate and cabin window perimeter compared to the painted exterior of the aircraft makes these areas look cooler because of the inaccurate emissivity setting which has caused the thermal camera software to report the door handle temperature as 18°C whereas the exterior of the aircraft is at 29°C. There are few metallic surfaces in the ERS training aircraft cabin. By themselves they would not obscure a heat source, as other materials surround them.

Fig. 13. SEEK visual and thermal pair of the ERS aircraft exterior at the L1 door.

6.1.2 THERMAL REFLECTION

The operator's body heat was observed as reflections in one instance where the cabin ambient was -4°F (-20°C). The operator's breath condensed on the interior panel surfaces making them reflective. In Fig. 14a the body heat of a person standing at the forward end of the cabin is seen in a false-colour image. The TIC settings were changed from false-colour to greyscale and a temperature threshold of 32°F (0°C) was set. These settings removed the distraction of the body heat reflections as shown in Fig. 14b, which was taken looking aft. In both figures, the heater strips at Site P1, P2 and S3 are energized. This issue, of thermal energy reflecting off an adjacent surface, was previously observed on an attic pipe above Site S3 in the un-powered ERS aircraft – Section 7.6.



a) False-colour thermal image

b) Grayscale, "White is Hot" with threshold

Fig. 14. FLIR T650sc thermal reflection.

6.1.3 SOLAR HEATING

Solar heating of cabin windows, their mechanical shades and adjacent side-wall panels has been observed in the un-powered ERS training aircraft. The mechanical window shades are both open and closed as marked (X) in Fig. 15. It is yet to be determined if solar heating of these same components will be observed in thermal views of a cabin during a daytime commercial flight. Air movement resulting from an operating Environment Control System (ECS) may mitigate some of the solar heating. Closing the mechanical blinds or dimming electric windows may still be preferred when scanning the cabin during a search for a hidden fire.

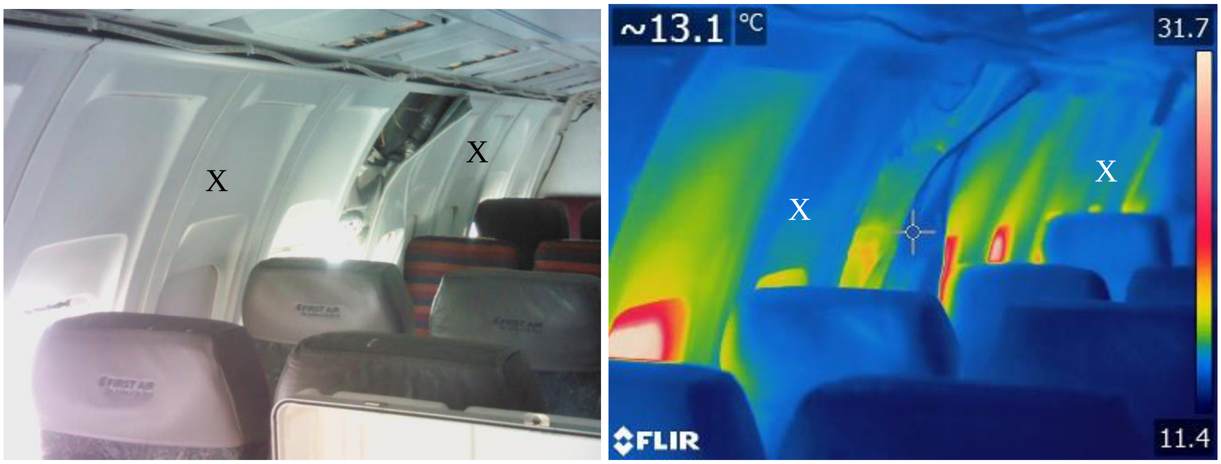


Fig. 15. FLIR T650sc solar heating visual and thermal image pair. Mechanical shades open and closed (X).

7.0 B737-200 THERMAL CAMERA TESTS

7.1 SITE P1 – OVER-HEAD LUGGAGE BIN

An electrical heater strip with both control and sensing thermocouples was adhered to the inner metal edge of the port overhead luggage Bin 18. The heater was set to ramp up to 40°C (104ºF) and is shown in Fig. 16. The actual heater setpoint compared to the temperature measured by the IR cameras is of no consequence since the objective is to simply create a hot spot for detection. A heater in an overhead bin could simulate a fire source which is pressed up against the outside edge of the bin or one deep inside a bag, which would be less apparent.

Fig. 16. P1 heater and TC installation in port Bin 18.

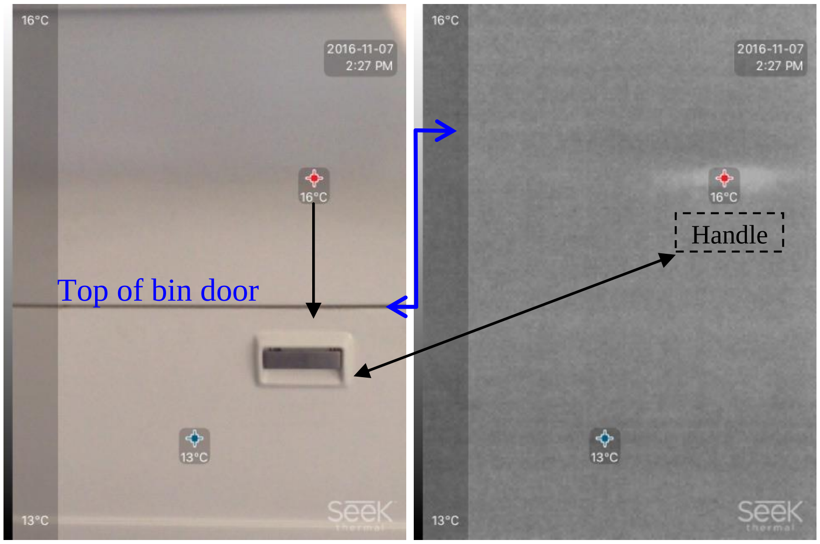


Fig. 17. SEEK Visual and Thermal image pair of Bin 18.

Fig. 17, taken within the confines of the centre aisle, shows a front view of the Bin 18 door when the heating has just begun and a temperature rise is first detected. In the thermal camera view, the Red (Hi) target is centred on the heater location (16°C). The Blue target locates the lowest temperature in the view (13°C). The two pictures were captured simultaneously but the position and Field of View (FOV) miss-match of the visual and thermal cameras is very pronounced in this close-up view. The miss-match displaces the superimposed Hi/Lo targets on the visible image. The operator does not see this on the display, it only appears on the stored visual image. Fig. 18 – 20 are pairs of optical and TIC images for both the FLIR T650sc and the SEEK Compact cameras, with and without smoke obscuration.

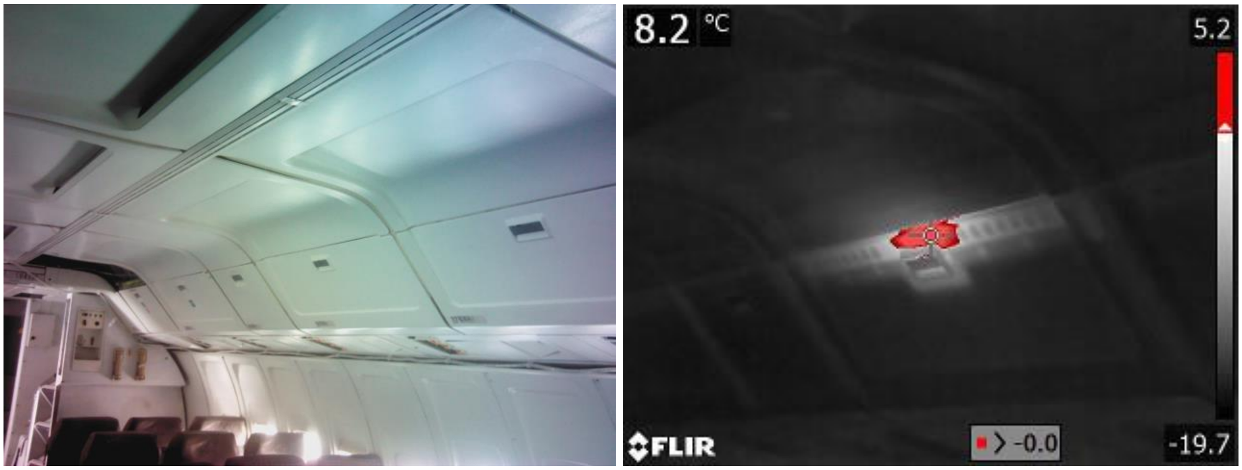


Fig. 18. FLIR T650sc visible and thermal image pair of Bin 18. Greyscale with threshold false-coloured.

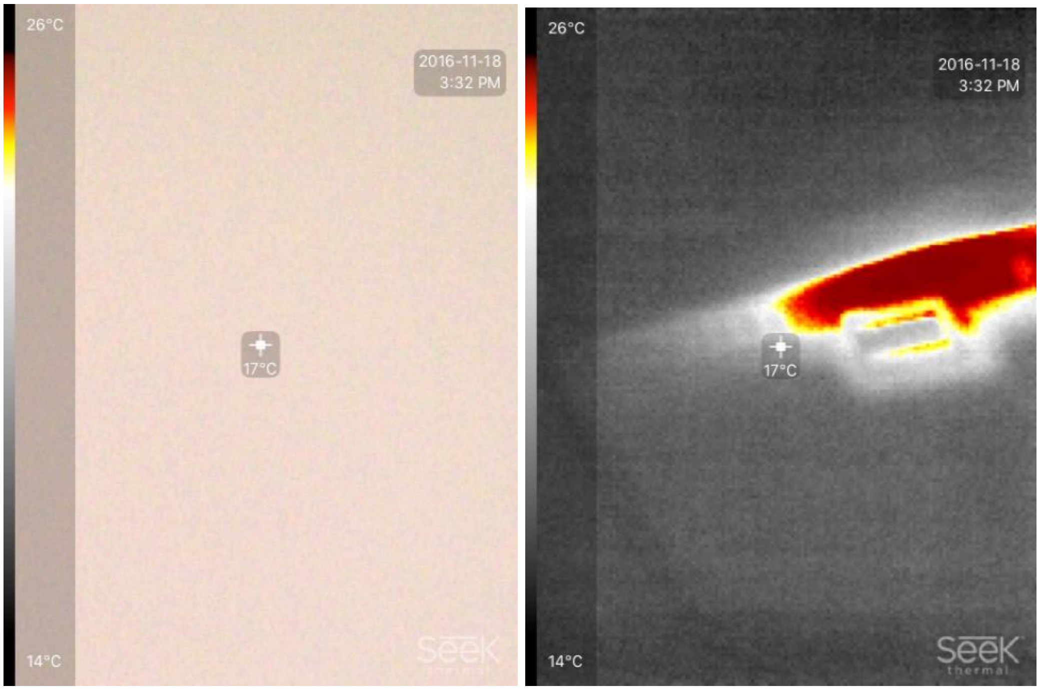
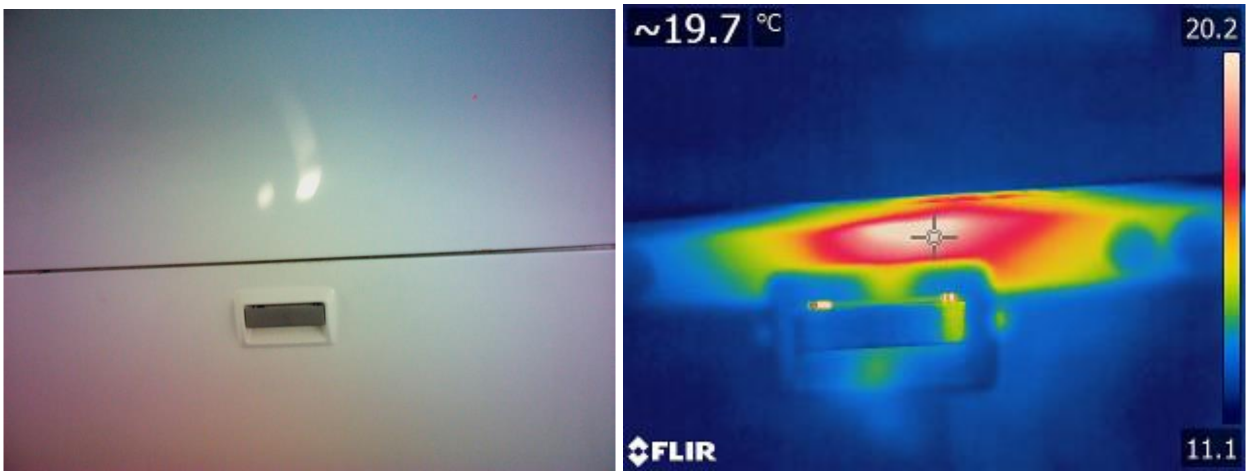
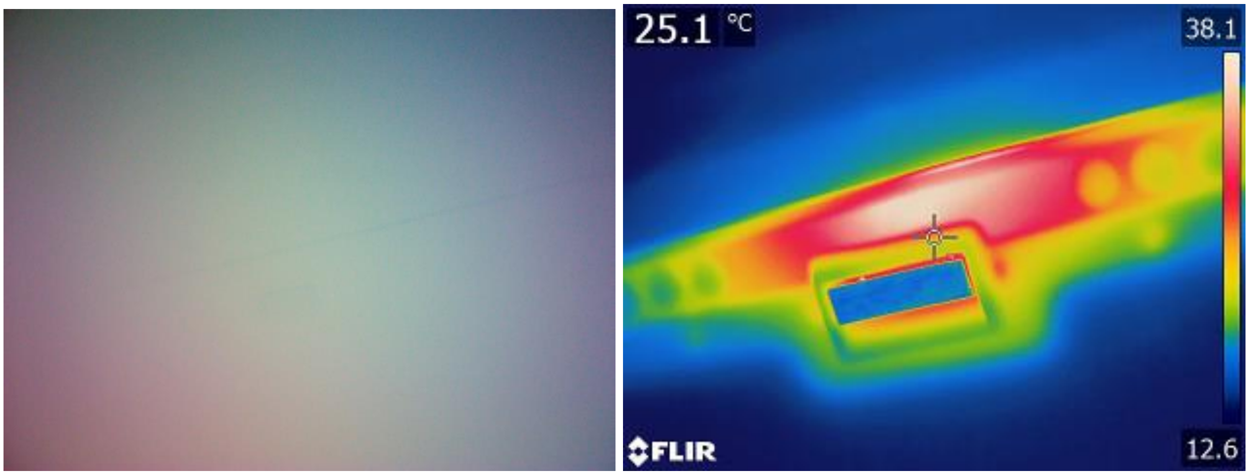


Fig. 19. SEEK Compact visible and thermal image pair of Bin 18 in fog.



a) FLIR T650sc Visible and Thermal image pair



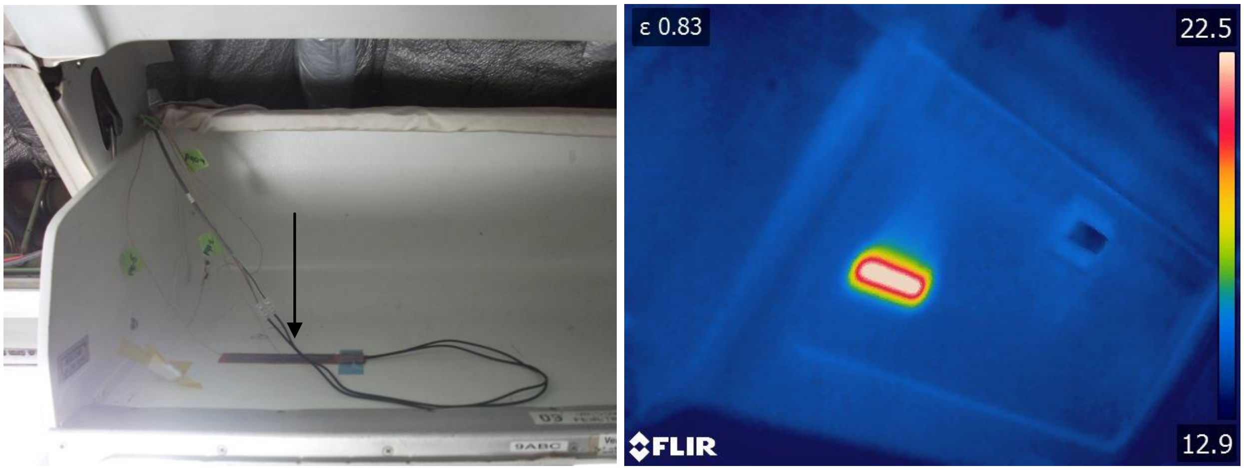
b) FLIR T650sc Visible and Thermal image pair in fog

Fig. 20. Close-up views of Bin 18, site P1.

7.2 SITE P2 – OVER-HEAD LUGGAGE BIN

This trial was very similar to Site P1 but with the heater strip mounted on the composite sandwich-construction bin door inner surface, as shown in Fig. 21a. Note that the emissivity setting (ε) was manually changed from the default 0.98 to 0.83 for the image in Fig. 21b.

The images in Fig. 22 were taken from the forward cabin and show Site P2 as the fog begins to fill the cabin and obscure the visual image. Site P2 is shown from the aft galley in Fig. 23.



a) Heater on inner surface b) FLIR T650sc Thermal

Fig. 21. Site P2 heater and TC installation in port Bin 9.

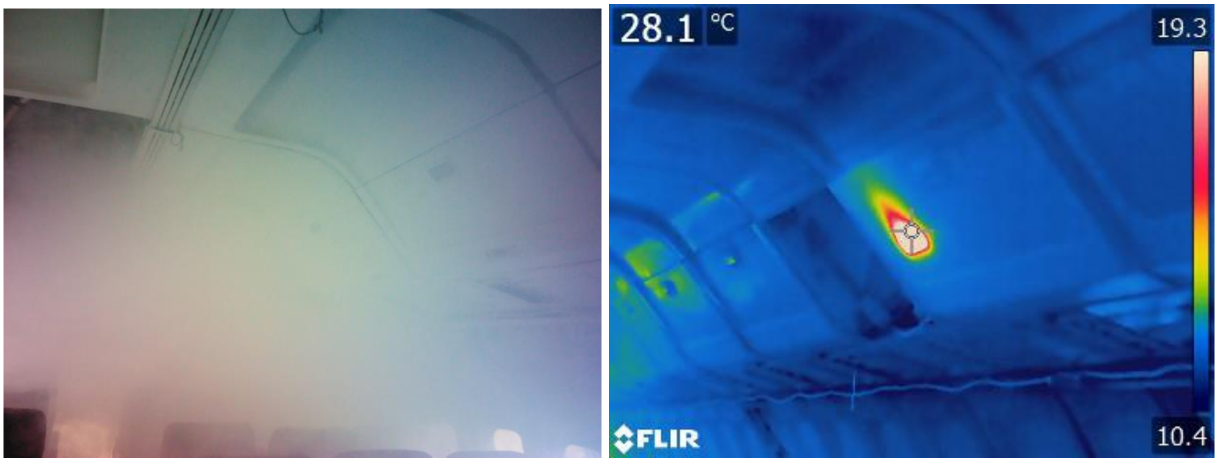


Fig. 22. Site P2 Visual and Thermal image pairs, from forward, in partial fog.

Fig. 23. Visual and Thermal image pair, from aft. Sites P2 and S3 marked.

7.3 SITE P3 – PASSENGER SEAT

There are five different seat constructions populating the cabin. Four types have cloth coverings and one is leather. Three have fabric seat pans while both the newest (2013) and oldest designs (1980) have a metal pan. The 1980s type used for the P3 site had a perforated metal seat pan as shown in Fig. 24b. An electric strip heater attached to a metal plate represented an overheating PED fallen behind or between seat cushions. The seat cushions may envelope and hide the PED from view while acting as an insulation layer above the heat source. The heater was set to 90ºC maximum.

a) Cloth covered seat b) Seat cushion removed - perforated metal pan

Fig. 24. Views of seat set with heater strip installed.

Early detection from the front side may be problematic due to there being an occupant or residual heat in the cushions after being vacated by the occupant, as illustrated in Fig. 25.

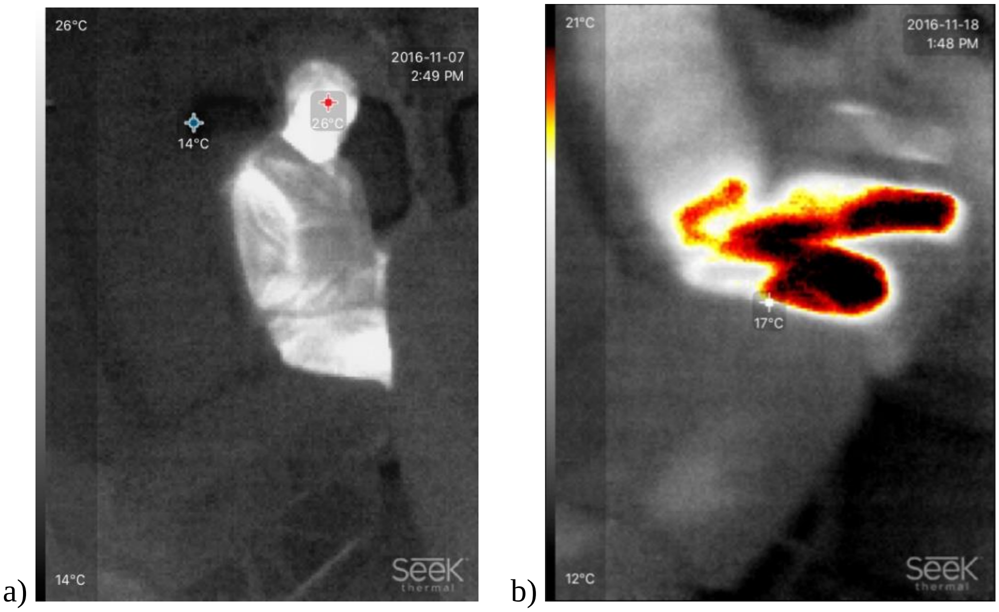


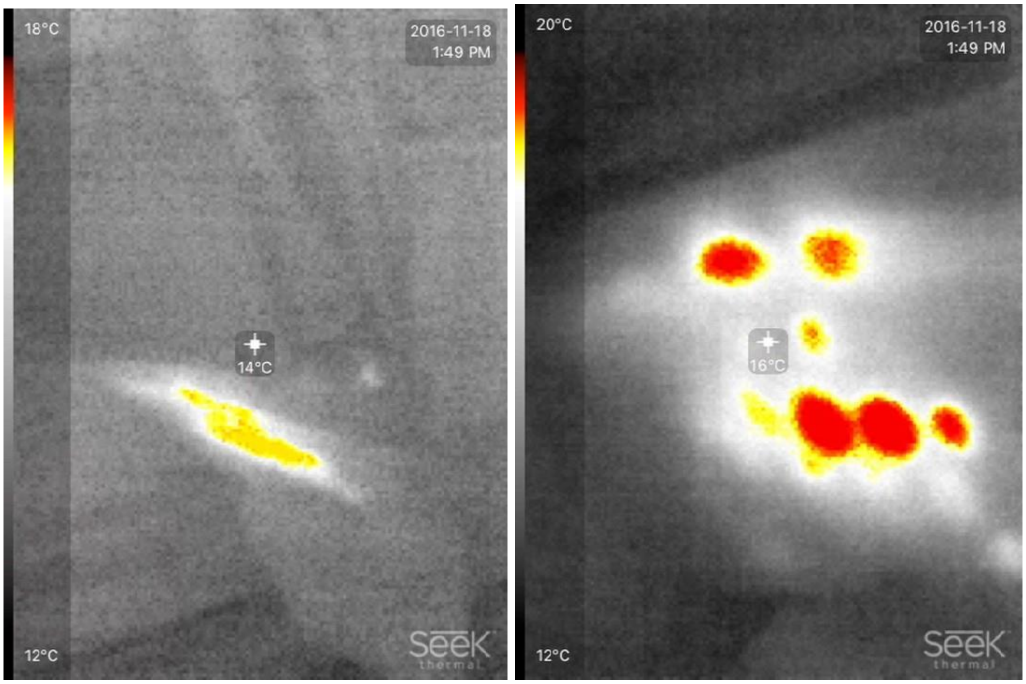
Fig. 25. SEEK thermal views of a seat occupied and recently vacated.

This concern lead to thermal views being captured from the seat row behind to explore this as a better viewing position. The seat has a plastic rear valance, which is shown in-situ and removed in Fig. 26. Detection from behind would not be affected by a passenger occupying the seat.

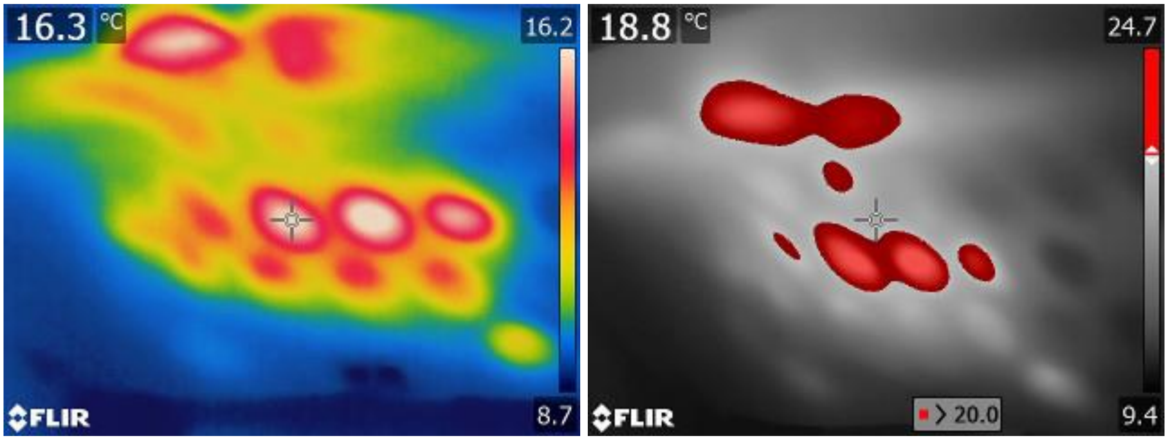
a) Seat back with plastic valence panel b) Seat back with valence panel removed

Fig. 26. Views of back side of seat set, site P3.

Fig. 27 shows four thermal views of heat affecting the rear valence as seen first from the aisle and then from more directly behind. Heat is radiating more directly onto the valance through the perforations in the seat structure.



a) SEEK thermal viewed from centre aisle b) Seat back viewed from behind



c) FLIR T650sc thermal d) Thermal with 20ºC threshold

Fig. 27. Thermal views of seat back lower valence, site P3.

Fig. 28 shows two TIC views with the heater between the back and seat cushions. The image was taken 13 minutes after the thermal image Fig. 25b was captured. Note that some residual heat from the occupant is still visible on the seat cushion in that view.

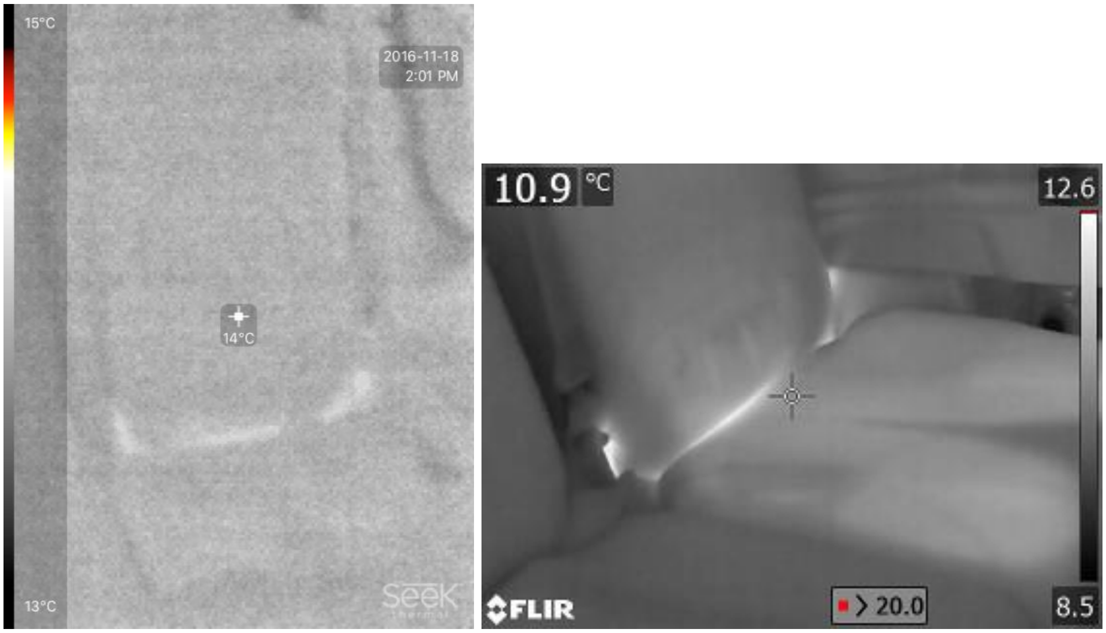
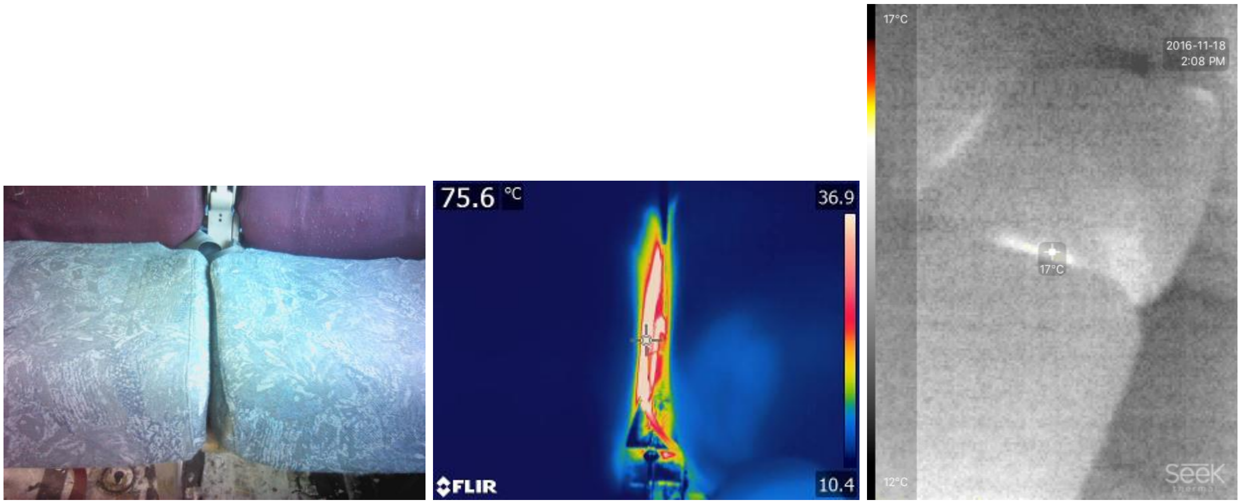


Fig. 28. SEEK and FLIR T650sc views of heater at rear of bottom cushion, site P3.

It was found that a heater located between adjacent seat cushions could be enveloped and insulated by the low thermal conductivity of the cushions, making detection in this location difficult. Thermal views from directly in front and also from the aisle are shown in Fig. 29.



a) Heater between cushions b) FLIR T650sc thermal c) SEEK thermal from aisle

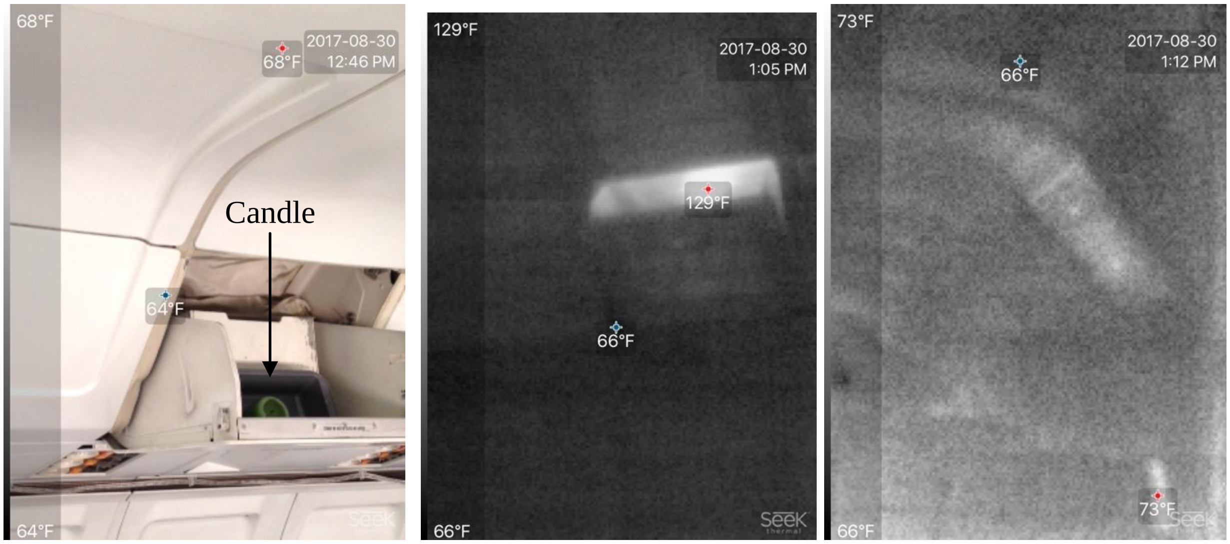
Fig. 29. Visual and Thermal views of heater between seat cushions, site P3.

7.4 SITE S1 – OVER-HEAD LUGGAGE BIN

A single wax candle was positioned in the bottom of starboard Bin 19, shown in Fig. 30a. The wax candle flame is nominally 850ºF (454ºC). The size of the heat source does not increase as it would in a real fire where, once ignition is reached, the fire would develop as it accessed more fuel. The bin is 15 inches (38.1 cm) deep but, with the bin closed, the top edge of the door is 4.4 inches (11.2 cm) below the highest point in the cavity. The top of the bin enclosure is a rigid panel material similar to the adjacent ceiling panel. The back side of the bin enclosure has a fabric secured around the perimeter by Velcro strips. The design of the bin results in the heat collecting in the top and affecting the ceiling panel directly above Bin 19.

By 4:11 minutes after lighting the candle, some of the bin door substructure (end-grain balsa blocks) could be discerned and even though the high and low temperatures in the view were only three degrees apart (68-73ºF). The bin was opened at the 5:05 mark. The peak internal temperature viewed with the SEEK TIC, on the back closure fabric, at this time was 149ºF (65ºC). Fig. 30b shows the bin open at 5:16. Note the bin door substructure read-through, possibly transmission through the end-grain of the balsa blocks.

The candle was burned for a total of 12 minutes, although the last overall thermal view of the bin exterior was captured at 11:29. In this view, shown in Fig. 30c, the temperature differential between the coldest (an adjacent ceiling panel) and the hottest (a solar heated cabin window) areas is only 7ºF (3.9ºC). The representation of the heated bin and ceiling panel is obvious in the thermal view, yet it is composed of temperatures within this small differential.



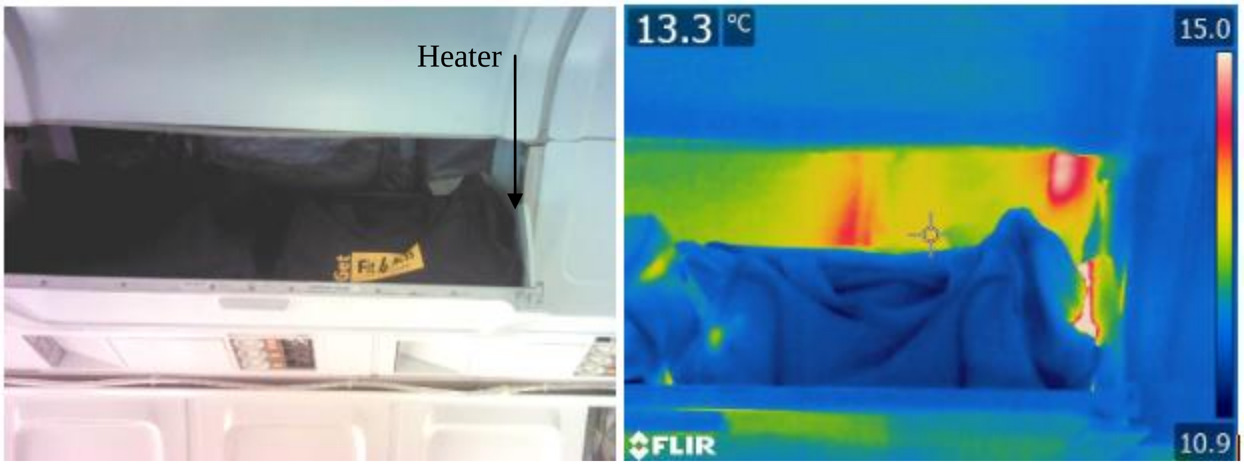
a) Bin 19, candle in metal pan b) At 5:16 Bin opened briefly c) At 11:29

Fig. 30. One lighted candle in bottom of port Bin 19, site S1.

7.5 SITE S2 – OVER-HEAD LUGGAGE BIN

An electric heater strip was placed on the sidewall of an over-head luggage bin, Bin 17. With the bin open the heater was easily detected thermally but when closed, the heating was not detected on the door exterior over the short duration of the test. Baggage was added in a second test, as shown in Fig. 31a. The bag obscured a direct thermal view of the heat source, but the heated air had risen and was detected on the upper inside and fabric rear surface of the bin cavity, as shown in Fig. 31b. This configuration was also imaged, early in the heating cycle, with the cabin filled with fog, shown in Fig. 31c.

a) FLIR T650sc Visual and Thermal image pair



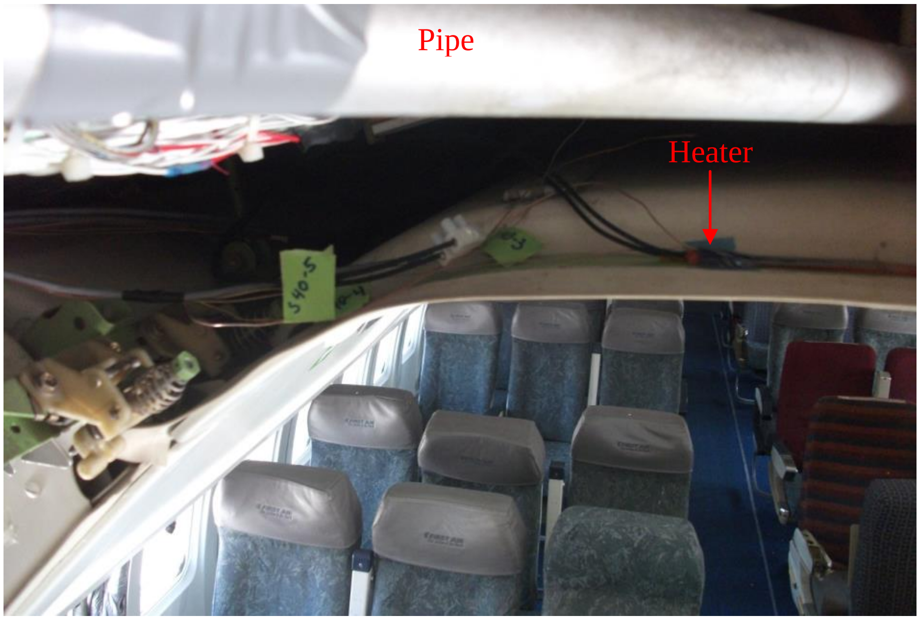
b) FLIR T650sc Visual and Thermal image pair, upper bin cavity heat

c) SEEK Visual with bin open d) Visual and Thermal views, heater energized in fog

Fig. 31. Visual and Thermal views of heating event in starboard Bin 17, site S2.

7.6 SITE S3 – CEILING PANEL

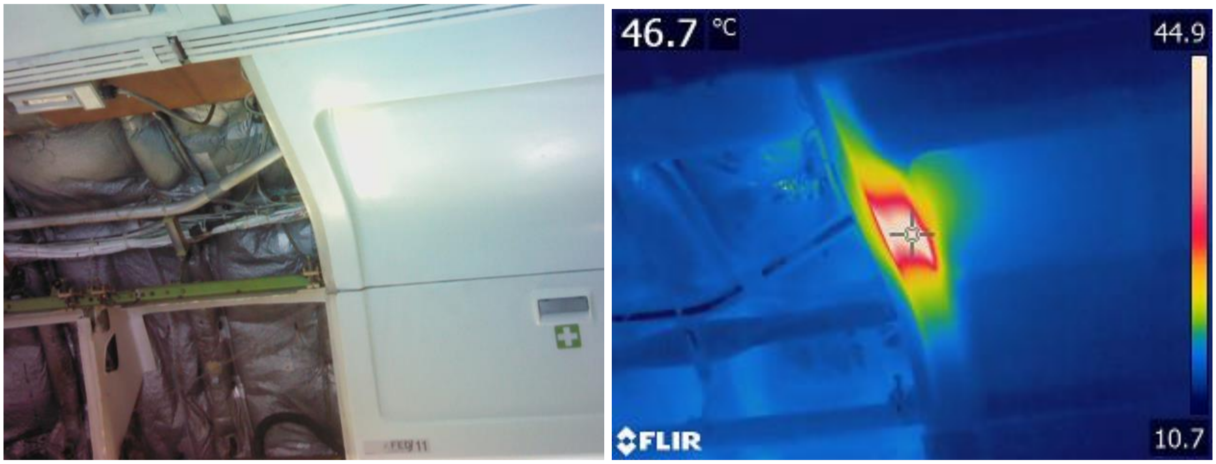
An electric strip heater was installed on the upper surface, forward edge, of the ceiling panel adjacent to starboard Bin 11, as shown in Fig. 32a. The adjacent ceiling panel was missing. With the heater energized and viewed from forward and into the exposed attic space, a metal pipe was found to reflect the radiant energy, as shown in Fig. 32b. This was one of the few instances where heat was reflected off of another surface that could potentially confuse the location of the actual heat source.



a) View of heater installation

b) SEEK Visual and Thermal images from below and from forward of Bin 11

Fig. 32. Site S3 Heater installation and SEEK Thermal views.



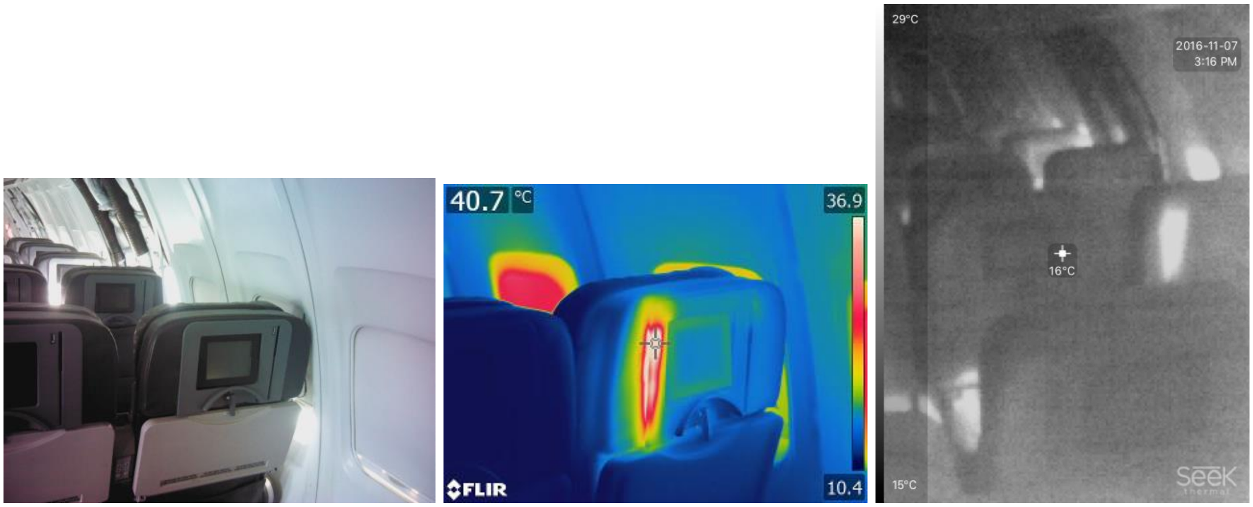
a) FLIR T650sc. From below

b) FLIR T650sc. From FWD

Fig. 33. Visual and Thermal image pairs of ceiling panel, site S3.

7.7 SITE S4 – PASSENGER SEAT-BACK DISPLAY

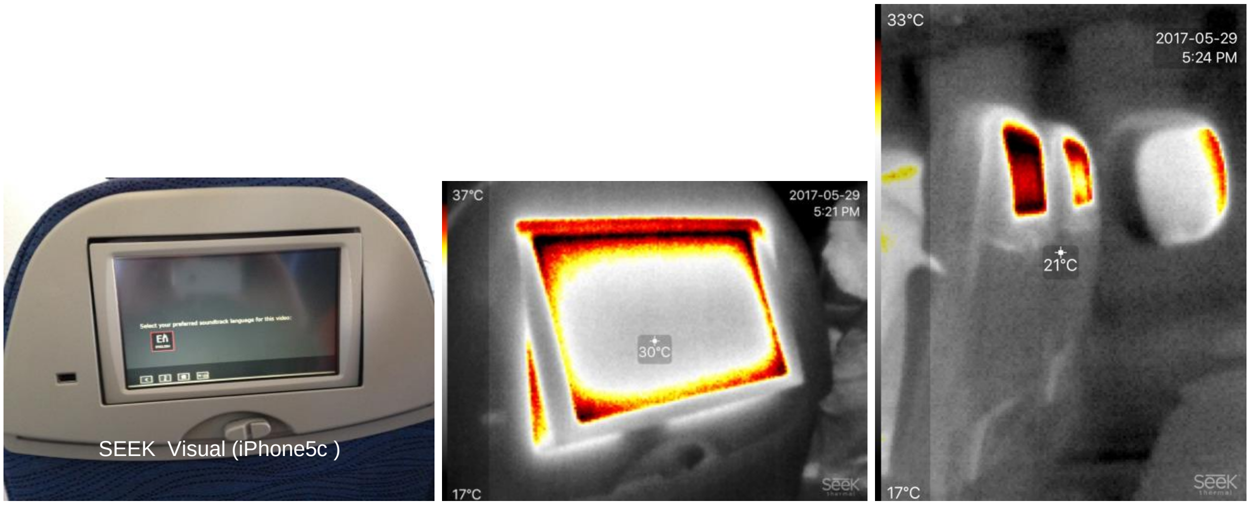
The simulated overheating of the electronics of a seat-back display was not tested in fog conditions. The surrounding material of one seat-back display on the un-powered ERS training aircraft was removed to install an electric heating strip under the plastic trim piece, which was then re-installed. With the heater strip energized, the FLIR T650sc measured a maximum temperature on the surface of the surround at 105.3ºF (40.7ºC). The SEEK thermal camera was also set to centre spot, which was located on the adjacent seat-back (ambient at 60.8ºF, 16ºC), as shown in Fig. 34. The highest temperature in the view was 84.2ºF (29ºC). The operator may not know if the highest temperature is the solar heating of the cabin window, but the seat-back heating would be unusual compared to the other seats in the view and thus draw attention.



a) Subject seat-back display b) FLIR T650sc Thermal c) SEEK Thermal

Fig. 34. Seat-back display with electric heater strip energized, site 4.

Visual and thermal images were captured of the normal operational condition of a seat-back display in-flight, as shown in Fig. 35. A threshold of 86ºF (30ºC) was set and those areas exceeding this temperature were false-coloured. The adjacent seat close-up image shows a maximum temperature of 98.6ºF (37ºC) while the view across the aisle of two identical displays shows a maximum of 91.4ºF (33ºC). The colourized area in the cabin window area may be a thermal reflection.



a) Subject seat-back display b) SEEK Thermal views of subject and adjacent displays

Fig. 35. Visual and Thermal views of operational seat-back displays.

7.8 SITE G1 – GALLEY COFFEE HEATER

On aircraft, the ovens and coffee machines are used to re-heat prepared foods. The coffee carafe is heated by an electrical element in the base of the unit. The electrical supply to the oven(s), coffee maker(s) and other appliances in the galley is through an adjacent circuit-breaker panel in the galley cabinet.

Fig. 36. Aft cabin galley area viewed from cabin, site G1.

A quartz halogen heat lamp was placed in the upper coffee maker bay of the aft starboard galley. The bottom partition of the upper bay showed evidence of minor heat damage as shown in Fig. 37. The lower bay has a metal sheet covering the surface and thus did not show any heat damage.

a) Aisle side of galley cabinet b) Coffee maker bays c) Heat damage on upper bay

Fig. 37. Aisle side view and coffee maker bays of aft starboard galley, site G1.

Fig. 38 shows the heat lamp energized and the corresponding SEEK thermal image. With both coffee makers in place, it would be difficult to detect an overheat of the upper unit while viewing from in front or below.

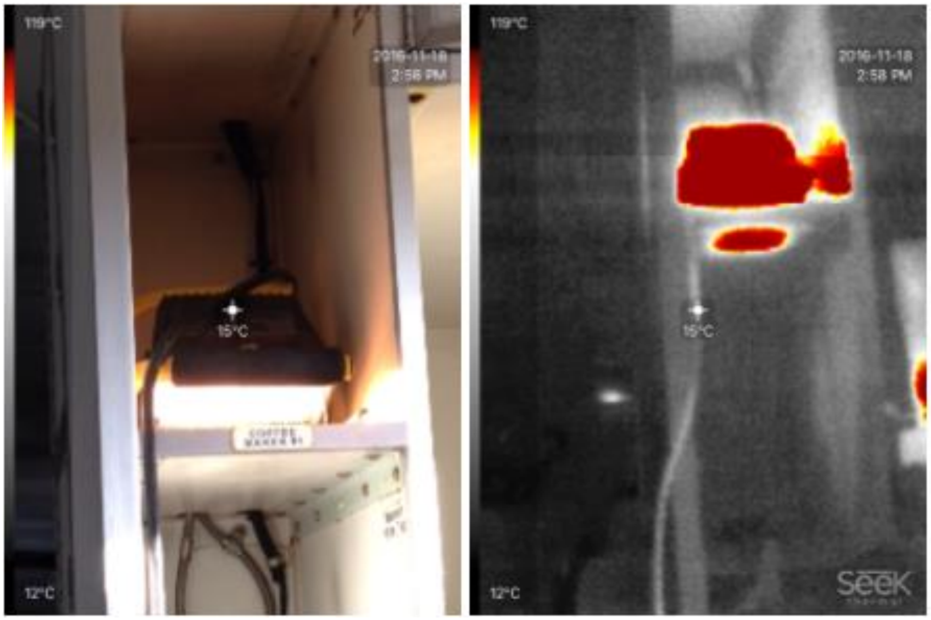
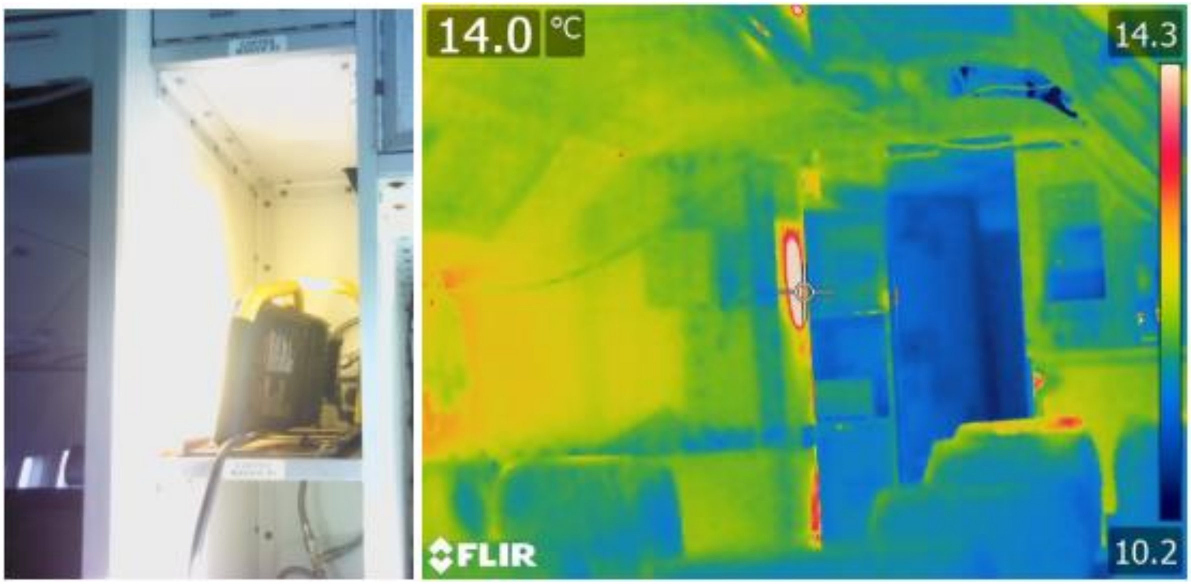


Fig. 38. Heat lamp effect on bottom partition of upper coffee maker bay, site G1.

The lamp was next oriented towards the aisle side-wall of the galley cabinet to determine if an overheating event could be more easily detected from the outside of the cabinet. It did not take long for the heat to be detected from a position forward in the cabin, as shown in Fig. 39.



a) Heat lamp in coffee maker bay b) FLIR T650sc Thermal view from cabin

Fig. 39. View of heated galley aisle-side wall, site G1.

This same test condition was also repeated after the introduction of fog, as shown in Fig. 40.

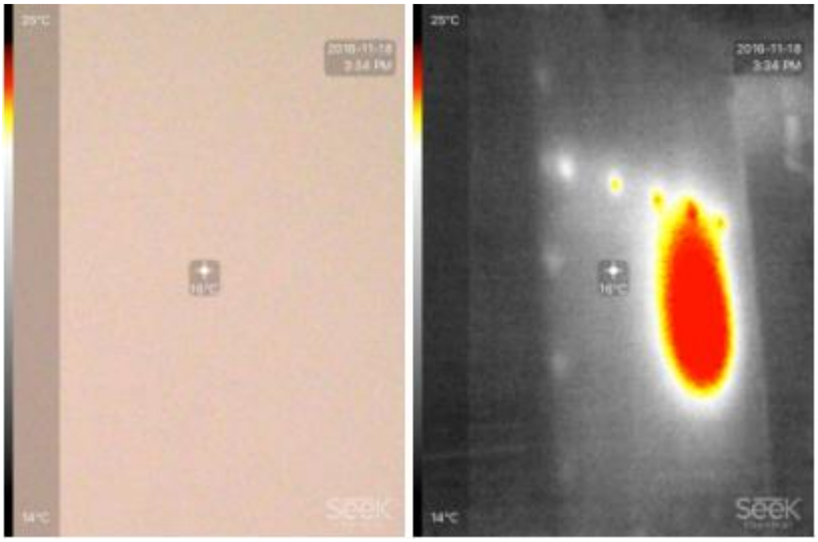


Fig. 40. SEEK Visual and Thermal image pair of coffee maker bay, in fog, site G1.

In some galley configurations there is a single coffee heater on an upper shelf with clear access to view the bottom surface. Fig. 41 illustrates such a configuration. The thermal image of the bottom surface of the upper bay in the ERS galley, heated with the heat lamp, illustrates the possibility to view the underside for overheat conditions.

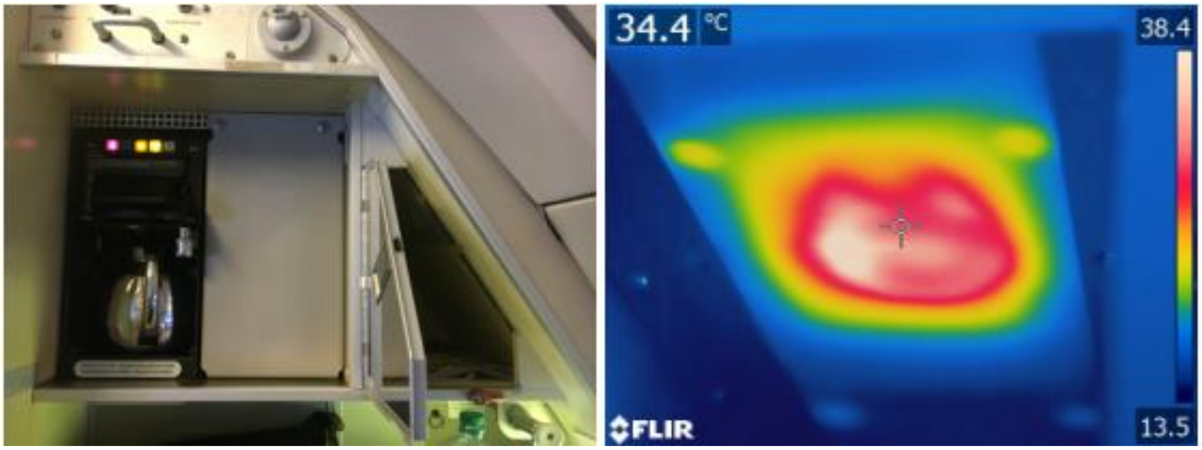
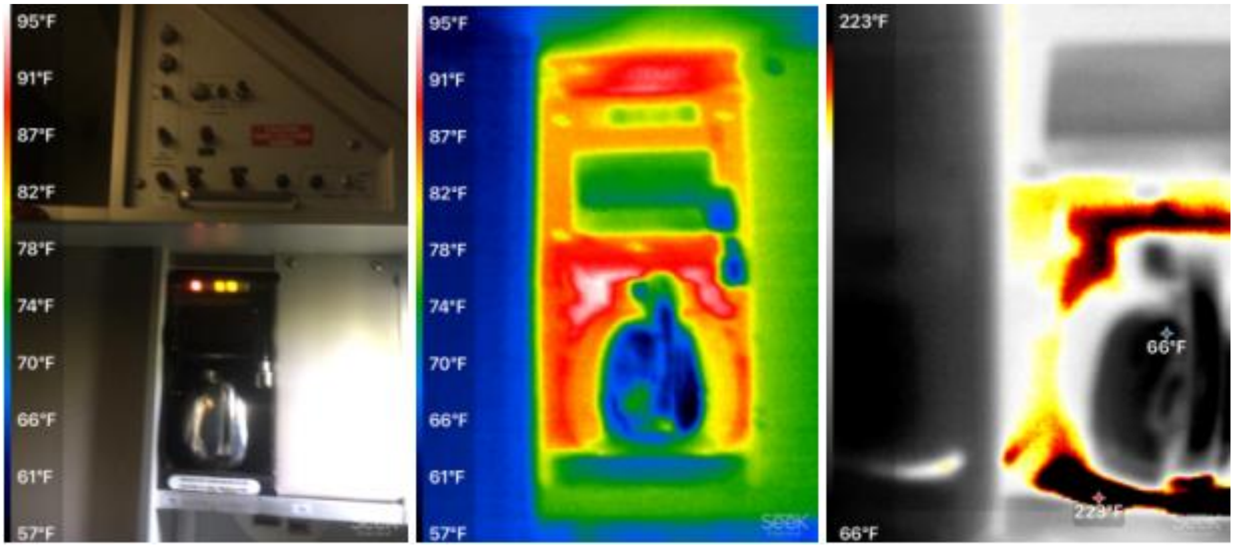


Fig. 41. Single coffee heater carafe in upper galley bay, site G1.

Normal operating temperatures of a galley coffee warmer were collected in-flight. The coffee warmer, shown in Fig. 42a and b, is cooling down after the heater element has been turned OFF. The heating element is ON in Fig. 42c, which is a greyscale image with a false-colour threshold set at 180°F (82°C) and the hottest area on the element is reported as 223°F (106°C). The carafe looks cold 66°F (19°C) due to the emissivity difference of stainless steel.



a) Visual, un-powered b)Thermal, false-coloured c)Thermal, threshold

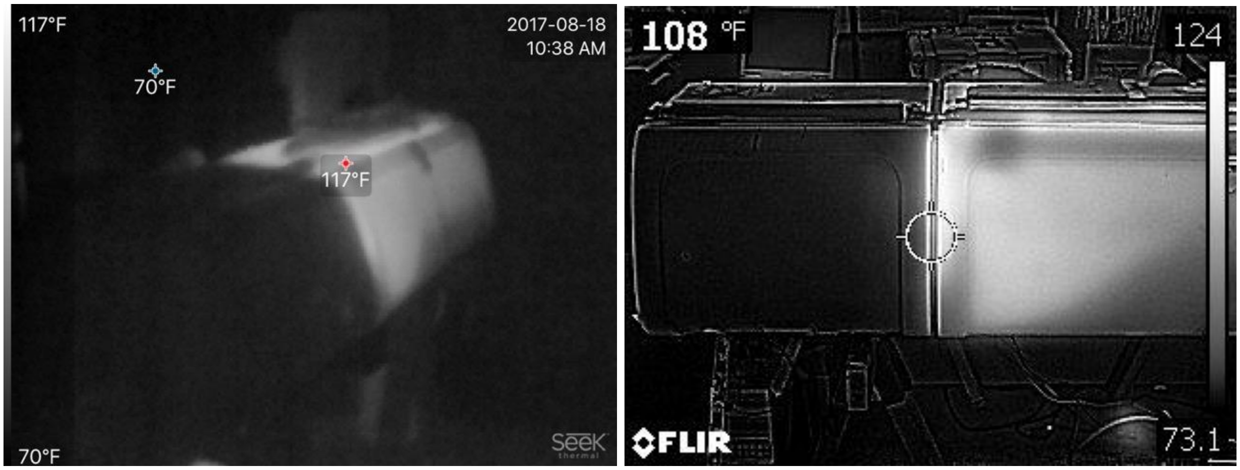
Fig. 42. SEEK Visual and Thermal views of powered coffee heater, site G1.

7.9 HEATED AIR – OVER-HEAD LUGGAGE BIN

Two, more modern, over-head luggage bins were tested in an NRC laboratory. A hot air gun was installed inside the bins. It was operated at maximum temperature (rated at 1040ºF, 560ºC). The air flow rate was not adjustable or measured. The door panel top edge is at the top of the bin cavity. Heat was first detected along these upper edges and between the doors where the heated air was escaping the bin.

The first overhead bin was two separate units on a common chassis, as shown in Fig. 43a. One bin was longer than the other. The heat gun was placed in the middle of the long bin, as shown in Fig. 43b. There is a gap between the end walls of the two bins. This thermal disconnect is evident in Fig. 43c, where the smaller bin is almost invisible, and in Fig. 43d, where the visible image edge-detection feature outlines the small bin.

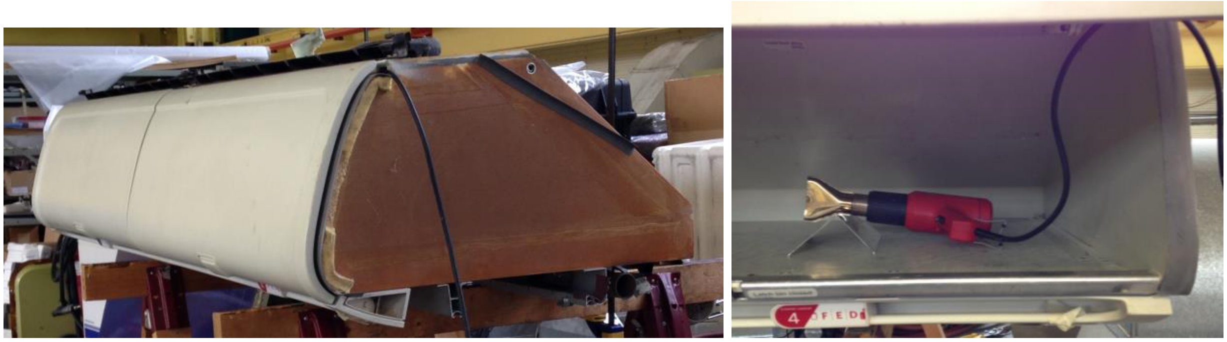
a) Overall view b) Longer bin, open, showing hot-air gun



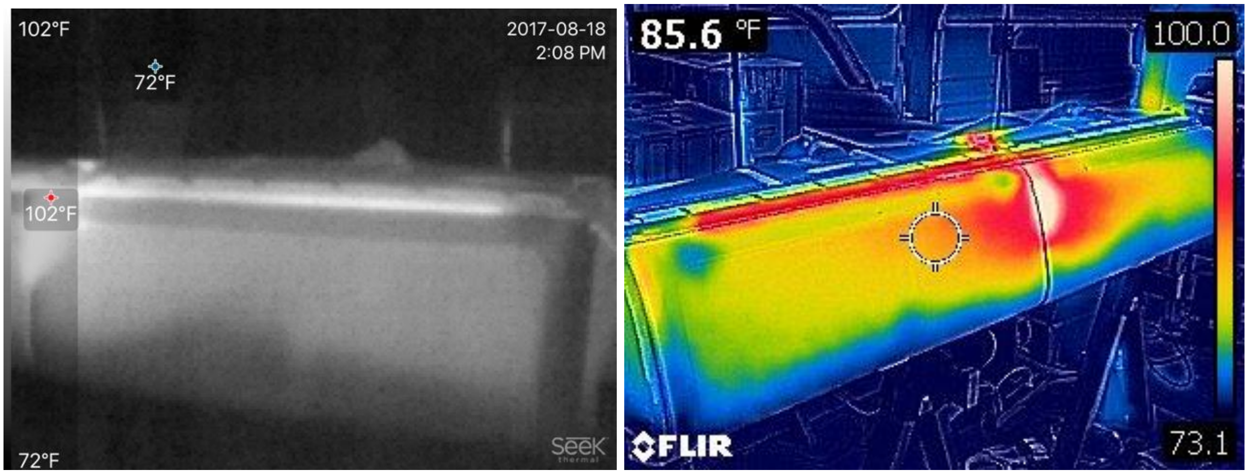
c) SEEK Thermal d) FLIR C2 thermal fusion

Fig. 43. Two-bin over-head luggage bin.

The second over-head luggage bin was one-piece with two equal-length doors, as shown in Fig. 44a. The heat gun was set to 50% (500ºF, 260ºC), located at the extreme right end and lower in the cavity, as shown in Fig. 44b. Fig. 44c shows the SEEK thermal view of the right hand door while Fig. 44d shows an overall view taken with the FLIR C2 TIC. The heated air escaped through the gap at the top of the left door. The highest temperature was at the gap between the two doors.



a) Overall view b) Hot air gun at right hand end



c) Heated air escapes along top edge, door joint d) FLIR C2 Thermal, bin overall

Fig. 44. Single bin with two doors and half-height internal divider.

In an aircraft, the conditioned air enters the cabin through diffuser ducts located on the top of the bins, as shown in Fig. 45a. Note the blower and that the bin doors are open and a ceiling panel is not in place in this image. Fig. 45b shows the set-up with the addition of a ceiling panel. To replicate the influence of the Environmental Control System (ECS), ambient room air (70ºF, 21.1ºC) was flowed through the diffuser with the blower. This diffuser airflow was operating at the time when Fig. 45c was taken, and illustrates how bins, where the top edge of the door are at the top of the bin cavity, will leak heated air that may first affect the cabin-side surface of ceiling panels immediately above. This is opposite to the candle heating in the older style bin, Site S1, where the ceiling panel was heated from the back side. Fig. 45c shows a similar configuration to Fig. 45d and is of an aircraft in-flight with cabin populated and conditioned air cooling the ceiling panels. In an operating aircraft, the heat rising from a bin fire will be mixed with the cooler air from the ECS airflow, which may delay or reduce the heating rate of the adjacent ceiling panels.

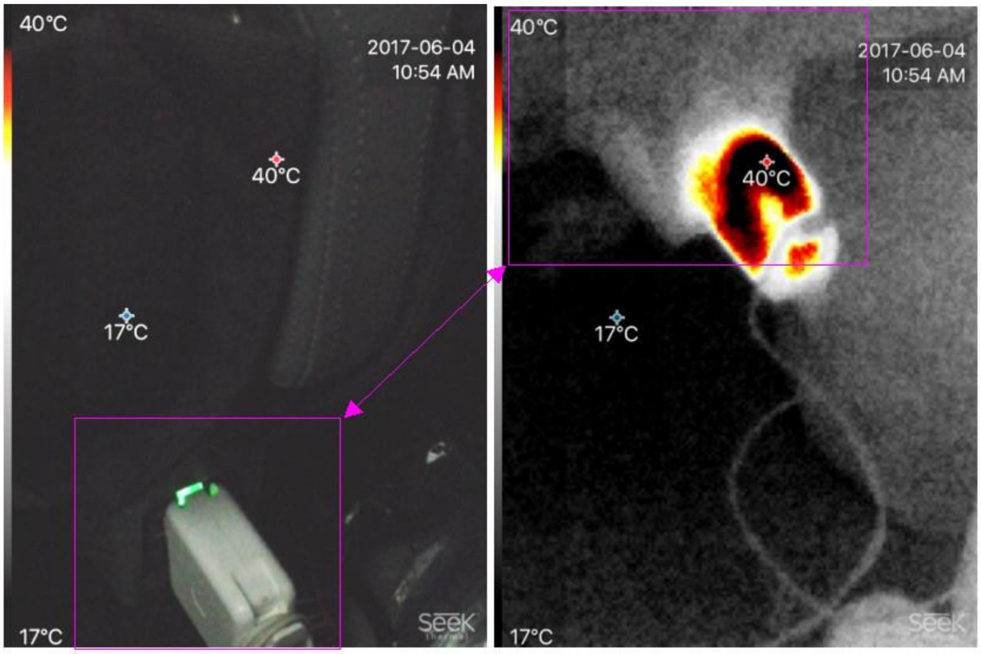
a) ECS diffuser ducts, blower. Bin doors open b) Ceiling panel added. Bin doors closed

c) SEEK Thermal, Hot air and ECS d) SEEK Thermal. Aircraft cabin in flight

Fig. 45. Cabin ceiling panel mock-up and in-flight.

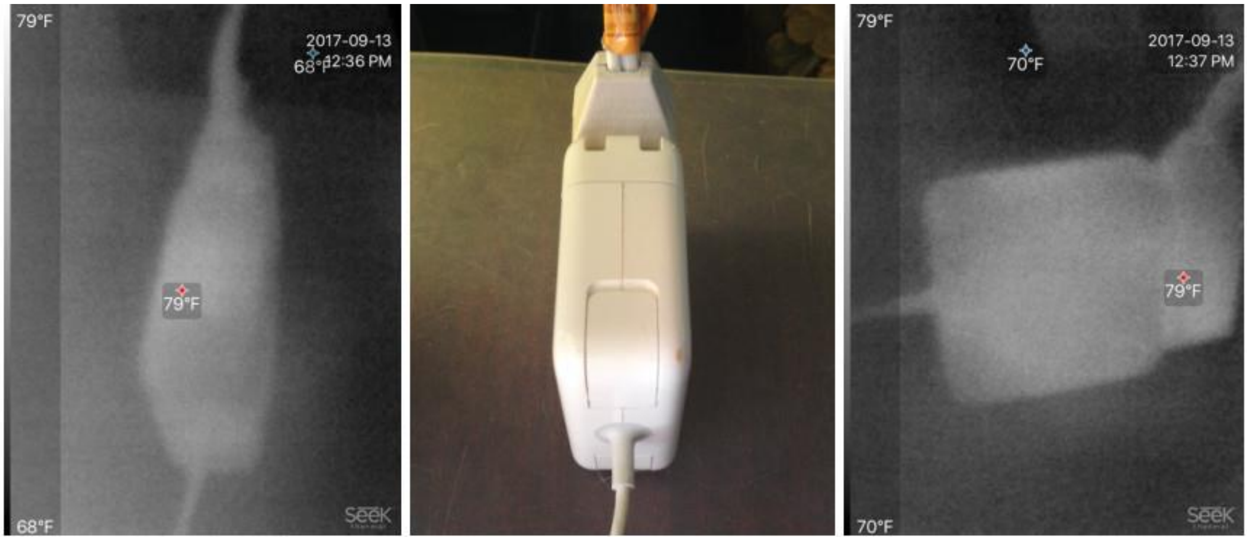
7.10 POWERED CABIN – IN-FLIGHT

On both a B777 and B787 aircraft (115 ṽ, 400 Hz) and at a hotel in Denmark (240 ṽ, 50 Hz) this Apple lap-top charger/power supply transformer ran uncomfortably hot to the touch (104ºF, 40ºC), as shown in Fig. 46a. On domestic 115 ṽ, 60 Hz the unit stabilizes at 79ºF (26.1ºC), as shown in Fig. 46b.



SEEK Visual and Thermal image pair

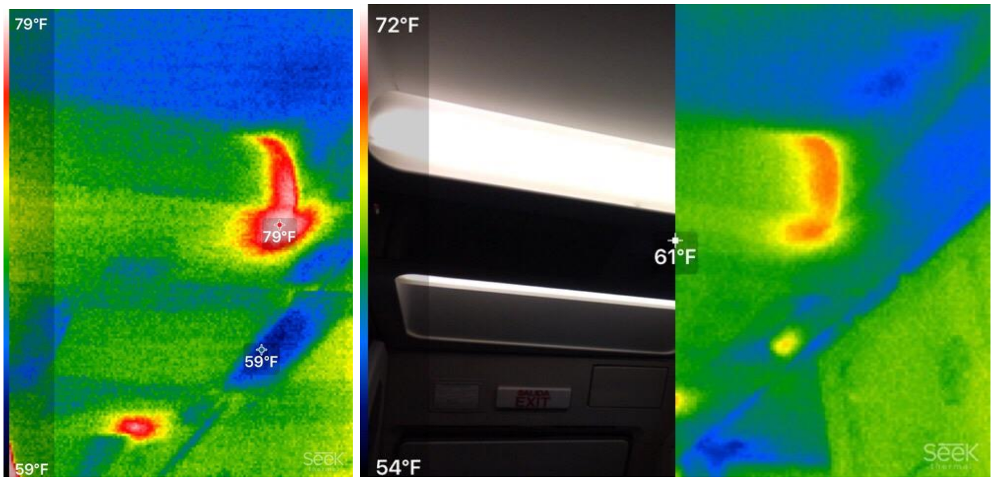
a) Laptop PED power supply plugged into aircraft seat-back 115 ṽ



b) Laptop PED power supply plugged into domestic 115 ṽ

Fig. 46. PED power transformer.

The vast majority of cabin lighting fixtures are fluorescent tubes powered by high-voltage ballasts, which may be co-located or remote from the fixture and behind the cabin panelling. The failure of ballast units [9] has caused smoke events and flight diversions. Comparison of energized lighting fixtures could aid in detecting ballast malfunctions. Fig. 47 shows two thermal views of a fixture under normal conditions.



a) Aircraft cabin ceiling fluorescent fixtures b) Split visual/thermal view

Fig. 47. Aircraft cabin ceiling fluorescent fixtures.

Aircraft lavatories are instrumented with smoke detectors and the waste bins have a dedicated fire suppression system. Electric hot water heaters and their control circuitry are not directly protected by the waste bin fire suppression system. A TIC may aid in locating an overheating / smoke event involving a water heater within the lavatory cabinetry, as shown in Fig. 48. Aircraft galleys may also have electric hot water heaters [10].

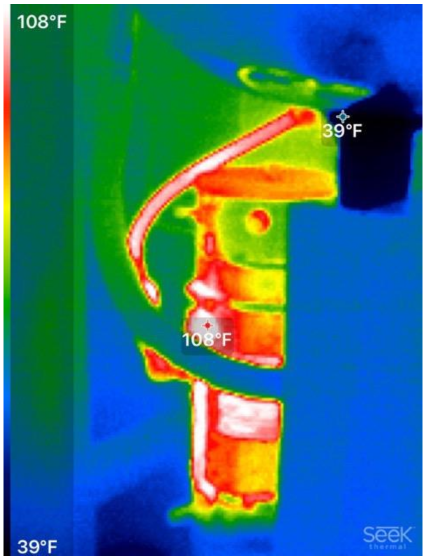
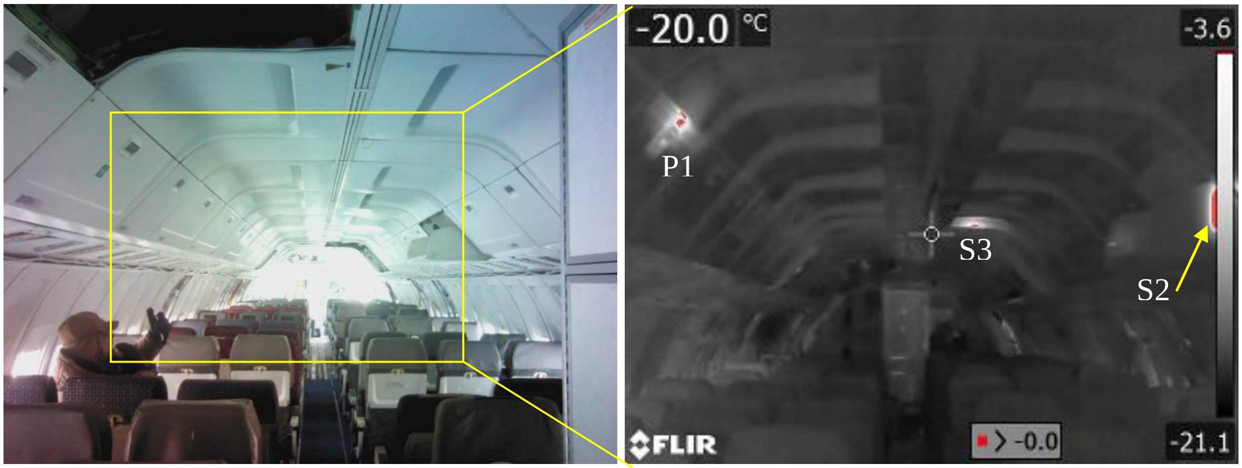


Fig. 48. SEEK Thermal view of energized lavatory water heater.

7.11 DETECTION FROM A DISTANCE

From the aft galley the TIC view in Fig. 49a shows three electric heat sources at Sites P1, S2 and S3. Note that at site S2 (starboard 18 Bin) is open. The distance from the aft galley to site P1 is 11.1 ft (3.4 m), to S2 is 9.6 feet (2.94 m) and the distance to S3 is 29.6 ft (9 m).

Sites P1 and S3 are shown in two thermal views, as shown in Fig. 49b, taken in fog from the forward cabin with the SEEK TIC. The distance between sites S3 and P1 is 18.5 ft (5.6 m). The distance from the camera to site S3 was not recorded, but was greater than 15 ft (4.6 m).



a) FLIR T650sc Visual and Thermal image pair looking forward from aft galley

b) SEEK Compact Thermal images, in fog, looking aft

Fig. 49. Electric heater strip test sites viewed from a distance.

8.0 THERMAL CAMERA APPLICATIONS

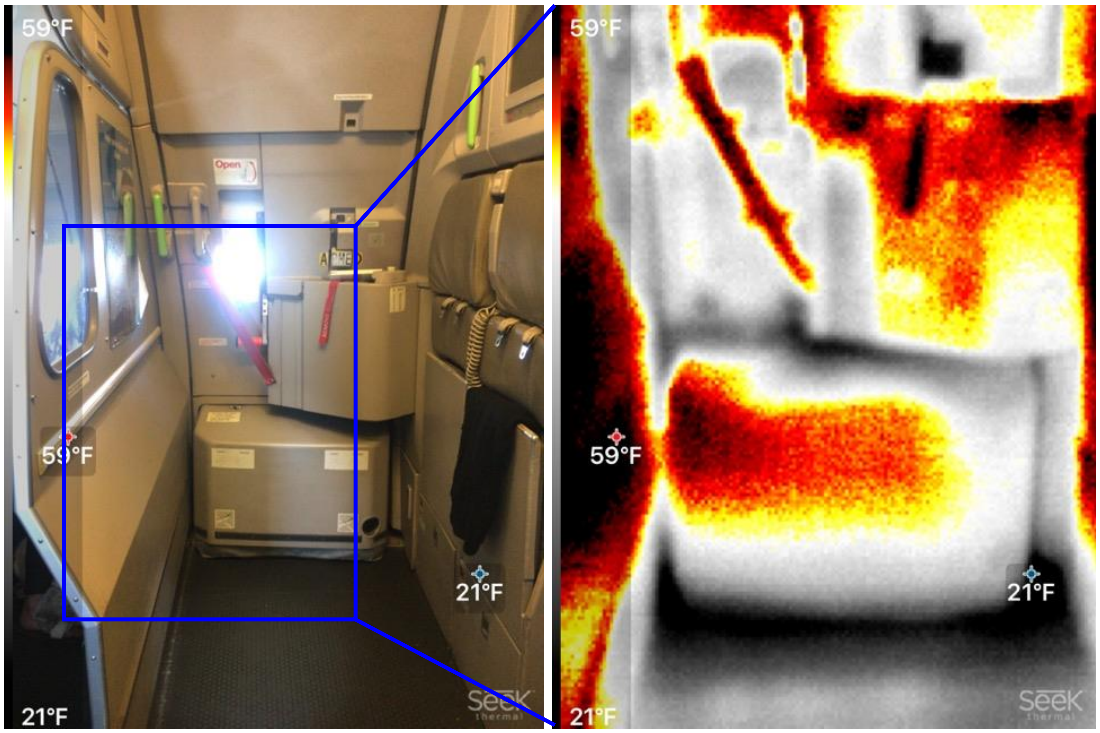
Low cost thermal cameras are being introduced into the market suggested as personal tools carried by each individual firefighter to help locate sources of fire and hot spots, as well as locating people.

A number of suppliers offer helmet-mounted TICs. Their displays are hand-held and thus viewing may be degraded when the environment is filled with smoke.

In some cases the camera display is located inside the SCBA mask faceplate thus eliminating any possibility of smoke interference for viewing the display.

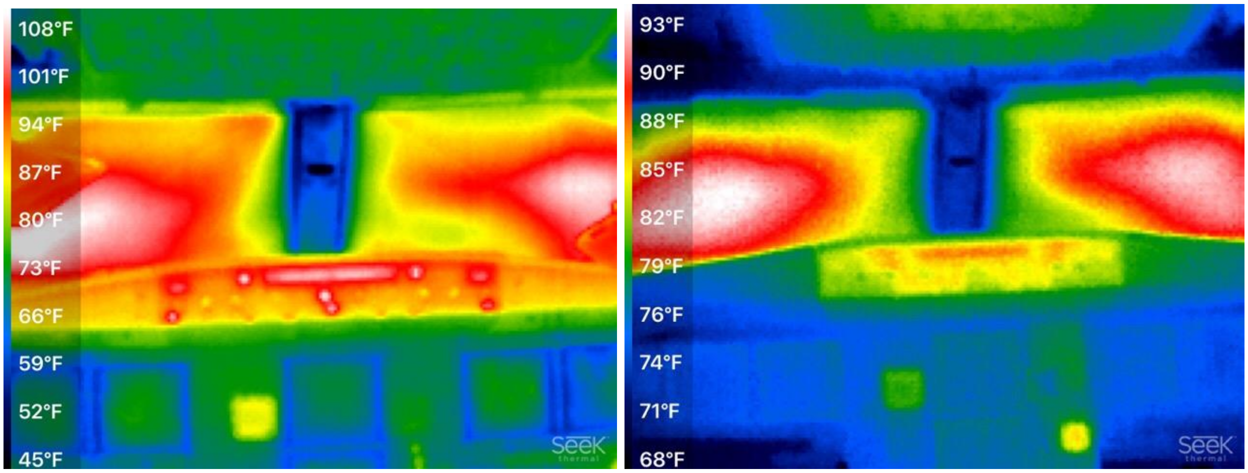
9.0 OTHER POTENTIAL USES OF THERMAL CAMERAS

1. Locating incapacitated passengers during an evacuation from a blacked–out or smoke-filled aircraft.
2. Screening passengers for onset of flu symptoms [11]
3. Once out on the ground, a TIC could assist in locating/assembling wandering passengers in bad weather or darkness.
4. Potential to detect a prone body covered in firefighting foam.
5. Potential to detect swimmer/floater in water, especially at night.
6. Detection of door seal air leaks. Reducing the potential for slow-onset hypoxia [12] as shown in Fig. 50.
7. Potential to detect/monitor cargo hold/under floor fires by viewing cabin floor.
8. Detect abnormal condition of heated windshields and electrically dimmable cabin windows prior to failure. Fig. 51 shows normal windshield conditions.
9. Detect overheating issues in cockpit instrumentation. Normal heating shown in Fig. 52.



SEEK visual and thermal views

Fig. 50. Potential to detect leaking aircraft door seal in-flight.



Cockpit in flight

Cockpit after landing, de-energized

Fig. 51. SEEK Thermal views of windshields in two aircraft cockpits.

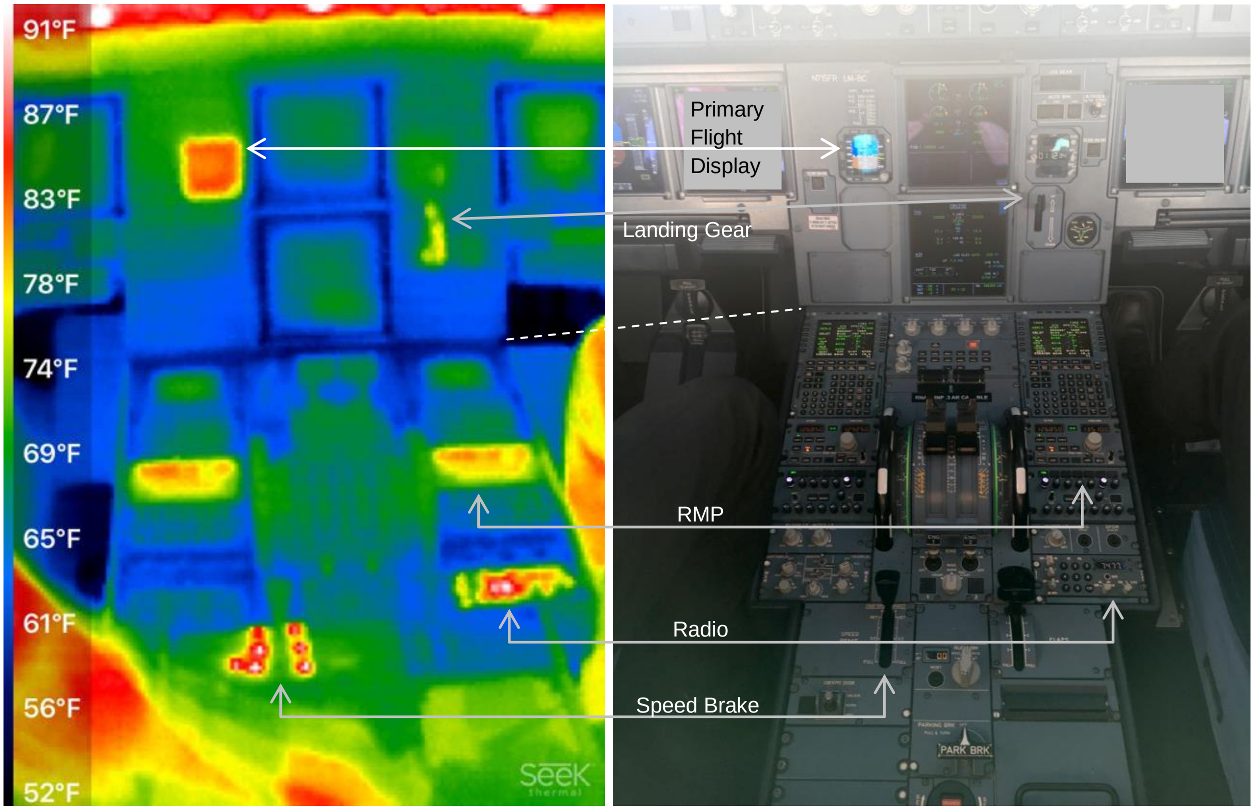


Fig. 52. SEEK Thermal and visual views. Centre Instrument Panel and Control Pedestal.

10.0 SUGGESTED MINIMUM DEVICE REQUIREMENTS

- Pocket size with adjustable lanyard (neck or wrist)
- One button ON/OFF
- Medium resolution IR sensor: 220 x 176
- 3 inch diagonal display
- 30 Hz refresh rate (SEEK Compact and FLIR C2 are 9 Hz and therefore do not require US DOC export licence)
- One pallet: “White is HOT”
- Auto emissivity
- Hi and Low temperature tags
- Still image capture with date stamp and Hi/Lo temperature tags
- Pre-set temperature threshold (false-colour exceeding temperatures)
- Rugged and water-resistant case
- High intensity light (replaces flight attendants’ flashlight)
- Noise generator (replaces flight attendants’ whistle)

11.0 CONCLUSIONS

Data generated during this project support the proposed idea of using thermal imaging cameras to detect hidden fires on aircraft. From the trial we have an indication that TICs can discern small differentials above normal cabin operational temperatures, even on surfaces distant from the heated locations and through composite sandwich panels. This suggests that anomalous heat events in confined spaces behind these panels can be detected.

None of the TICs employed should be considered optimized for the envisioned task of detecting hidden fires on aircraft. The SEEK Compact has some good features, but it first has to be connected to a phone, initialised by selecting an app once the phone is started and then wait for the self-calibration. The external TIC module is mounted via the phone's charging port, which is too fragile for everyday use. The FLIR C2 represents a good physical size with most of the features required. The FLIR T650sc was used as the reference tool for its high resolution imagery and software capabilities, but was never intended as a candidate device due to its size, cost and largely unused capability.

Smoke will obscure normal vision while cabin airflow will distribute the smoke away from the source and likely confuse and delay rapid detection of the location without the aid of heat sensitive visualization capabilities.

Cabin crews are expected to monitor the remains of a fire incident to guard against re-ignition. A TIC would be a valuable aid in providing critical metrics (quantitative data) to this evaluation.

To set a threshold for warning of an overheating condition, the normal peak operational temperatures must be determined. These typical thermal images would be used to educate and train cabin crew to recognize overheat and fire conditions. This capability would greatly reduce the potential confusion of system heat sources operating at their normal temperatures, although training to recognize normally continuous or periodic high heat sources would still be required. This alarm threshold might be set nearer ignition temperatures.

Access to an operational aircraft in-flight with a passenger load would provide normal operational temperatures of systems in the cabin seat sets, liner sidewalls and ceilings, such as, power distribution terminal strips/junctions, lighting units and ballasts, electrically dimmable windows, seat armrest and seatback control/power distribution, seatback display screens and entertainment hubs in overhead bins or under seats.

The next step would be to establish the baseline thermal signature for an aircraft with systems running. This could be done for individual systems and power configurations such as those applicable to loading or unloading on the ground up to in-flight conditions with appropriate lighting conditions, power to seatback audio/visual systems and galley equipment operation. At the same time it would be most beneficial to have trained cabin crew assess the use of a TIC and the collection of baseline thermal data could be that opportunity. These data would remain critical towards establishing a temperature threshold. NRC's Cabin Comfort and Environmental Research Facility could be used to generate additional data.

The use of a TIC onboard an aircraft is not restricted to the passenger cabin. The cockpit windshields, instrumentation in the centre console and dashboard along with the power distribution panels at the cockpit bulkhead are areas that have suffered overheat from component failure, high resistance terminals (loose connections) and cooling fan failures. Thus it is suggested that a TIC be used to aid in failure detection and maintenance actions.

The commercial airline community (as well as others) could greatly benefit from this work. Applying thermal imaging cameras to the task of hidden fire detection on aircraft has the strong potential to decrease search times and increase overall firefighting effectiveness. This work could rewrite standard operating procedures and equipment carried by airlines. The use of TIC cameras onboard aircraft would likely increase the general safety of the travelling public.

12.0 ACKNOWLEDGEMENTS

Mr. Saša Muradori from the Aerospace Research Center assisted in the installation of the electric heaters and thermocouples.

Mr. Dmirtrii Klishch from the Aerospace Research Center conducted the stand-alone luggage bin tests with a hot air gun as the heat source.

The authors also thank those firefighters of the OIAA ERS who participated in the site detection exercise with the cabin filled with fog.

13.0 REFERENCES

[1] R. Gould, F. Jacquet, S. Hind, "ARFF Special Projects", *ARFF Working Group*, *Future Aviation Safety – A Global Conference*, June 1-2, 2017. Copenhagen, Denmark.

[2] http://www.consumerreports.org/product-safety/whats-behind-the-increase-in-lithium-ion-battery-fires-on-planes/

[3] TSB "Interim Aviation Safety Recommendations - Thermal Acoustical Insulation Materials". Appendix A: accident synopses represent selected occurrences in which metallized PET insulation blanket cover material was involved and Appendix B: where metallized PVF insulation blanket cover material was involved.
https://www.tc.gc.ca/eng/civilaviation/opssvs/air-tsb-1999-a98h0003a-appendix-a-737.htm

[4] Most recent Incident: 21 Feb 2017, Azul E195. Cabin side wall overheats and catches fire. The occurrence is being investigated by Brazil's CENIPA.
http://avherald.com/h?article=4a547371&opt=0

[5] Most recent Incident: 2 Aug 2017, Lufthansa A388. Heavy electrical smoke/fire underneath passenger seat 10C. Passenger power bank stuck in the seat mechanism. 3 extinguishers used.
http://avherald.com/h?article=4acacb9f

[6] Most recent Incident: 23 may 2017, PIA B772. Smoke in galley. Flight diverted. Oven overheated and caused a fire. http://avherald.com/h?article=4a95e793&opt=0

[7] Most recent Incident: 20 Aug 2014, Air Canada B767-300, smoke and a burning smell in the cabin. The aircraft returned to Vancouver and requested ARFF. The company determined that the source of the smoke and smell was a coffee pot. http://canadianaviator.com/coffee-pot-emergency/

[8] AAIB accident report AAR 2/2015 - Boeing B787-8, ET-AOP Section 1.15.1, pg 38.

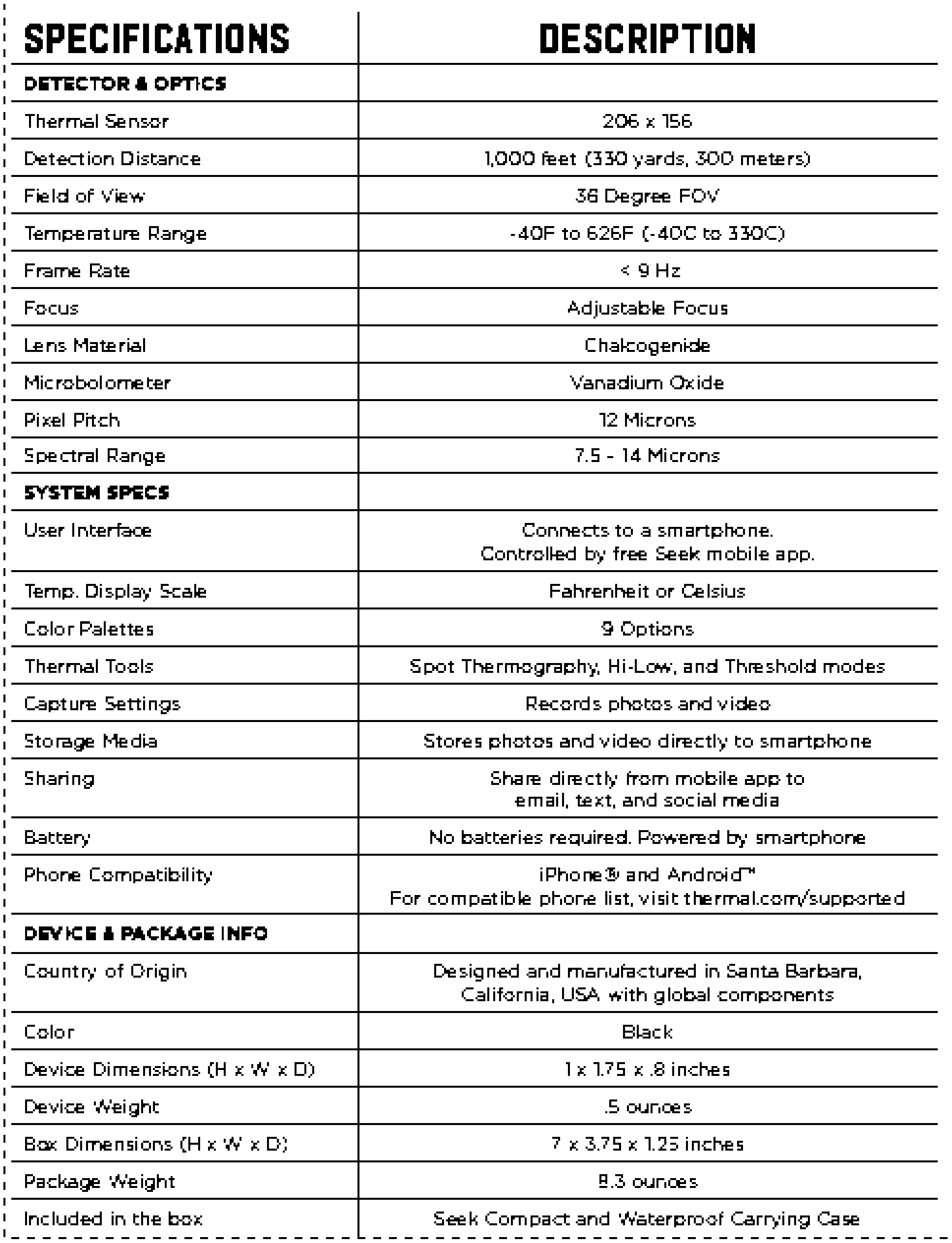
[9] Most recent Incident: 15 Sept 2017 Air Canada B767-300. Electrical burning odour in the cabin. Canadian TSB reported that "that the overhead light ballast between rows 13 and 14 was showing signs of overheating”. https://www.aeroinside.com/item/10298/canada-b763-near-toronto-on-sep-15th-2017-electrical-burning-odour-in-cabin

[10] Most recent Incident: 24 Jul 2016 Transasia A320-200. Smoke emanated from the aft galley. Cabin crew shut the galley power down, identified the water heater as the source of the smoke and discharged a Halon fire extinguisher. B/E Aerospace Inc., subsequently released a service information letter, No. H0212-25-0245, on February 28, 2017 for the power module assembly. Taiwan's ASC final report dated July 2017.
http://avherald.com/h?article=49bc5d40&opt=0

[11] New standards for fever screening with thermal imaging systems
http://iopscience.iop.org/book/978-0-7503-1143-4/chapter/bk978-0-7503-1143-4ch5
“the thermal imaging of the eye region being the most rapid non-contact site for measurement.”

[12] http://aviationweek.com/business-aviation/recognizing-and-preventing-slow-onset-hypoxia

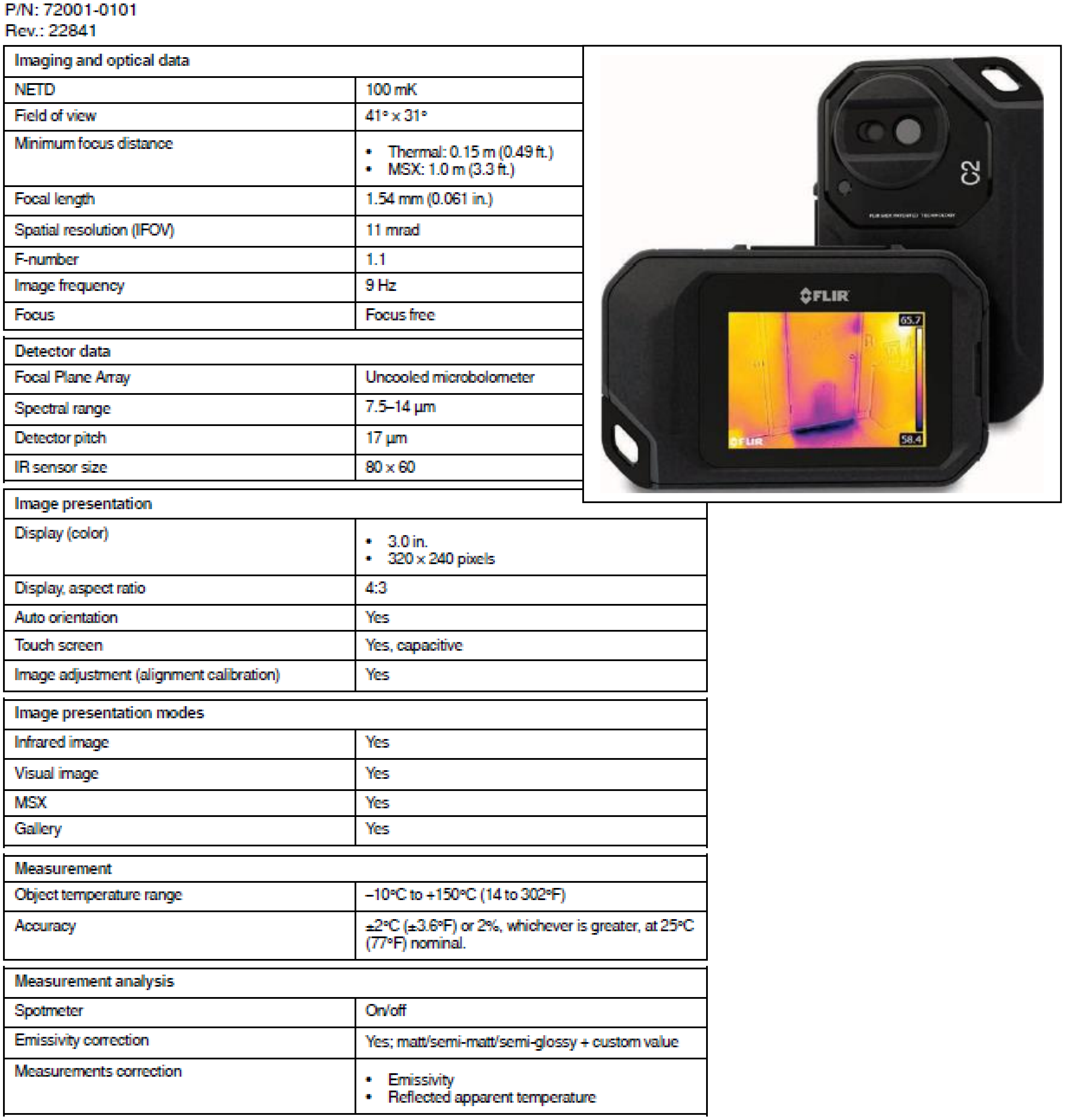
APPENDIX A: THERMAL IMAGING CAMERA SPECIFICATIONS



SPECIFICATIONS	DESCRIPTION
DETECTOR & OPTICS	
Thermal Sensor	206 x 156
Detection Distance	1,000 feet (330 yards, 300 meters)
Field of View	36 Degree FOV
Temperature Range	-40F to 626F (-40C to 330C)
Frame Rate	< 9 Hz
Focus	Adjustable Focus
Lens Material	Chalcogenide
Microbolometer	Vanadium Oxide
Pixel Pitch	12 Microns
Spectral Range	7.5 - 14 Microns
SYSTEM SPECS	
User Interface	Connects to a smartphone. Controlled by free Seek mobile app.
Temp. Display Scale	Fahrenheit or Celsius
Color Palettes	9 Options
Thermal Tools	Spot Thermography, Hi-Low, and Threshold modes
Capture Settings	Records photos and video
Storage Media	Stores photos and video directly to smartphone
Sharing	Share directly from mobile app to email, text, and social media
Battery	No batteries required. Powered by smartphone
Phone Compatibility	iPhone® and Android™ For compatible phone list, visit thermal.com/supported
DEVICE & PACKAGE INFO	
Country of Origin	Designed and manufactured in Santa Barbara, California, USA with global components
Color	Black
Device Dimensions (H x W x D)	1 x 1.75 x .8 inches
Device Weight	.5 ounces
Box Dimensions (H x W x D)	7 x 3.75 x 1.25 inches
Package Weight	8.3 ounces
Included in the box	Seek Compact and Waterproof Carrying Case

Source: http://www.thermal.com/compact-series.html

Appendix A 1. SEEK Compact specifications.



P/N: 72001-0101
Rev.: 22841

Imaging and optical data	
NETD	100 mK
Field of view	41° x 31°
Minimum focus distance	• Thermal: 0.15 m (0.49 ft.) • MSX: 1.0 m (3.3 ft.)
Focal length	1.54 mm (0.061 in.)
Spatial resolution (IFOV)	11 mrad
F-number	1.1
Image frequency	9 Hz
Focus	Focus free

Detector data	
Focal Plane Array	Uncooled microbolometer
Spectral range	7.5–14 µm
Detector pitch	17 µm
IR sensor size	80 x 60

Image presentation	
Display (color)	• 3.0 in. • 320 x 240 pixels
Display, aspect ratio	4:3
Auto orientation	Yes
Touch screen	Yes, capacitive
Image adjustment (alignment calibration)	Yes

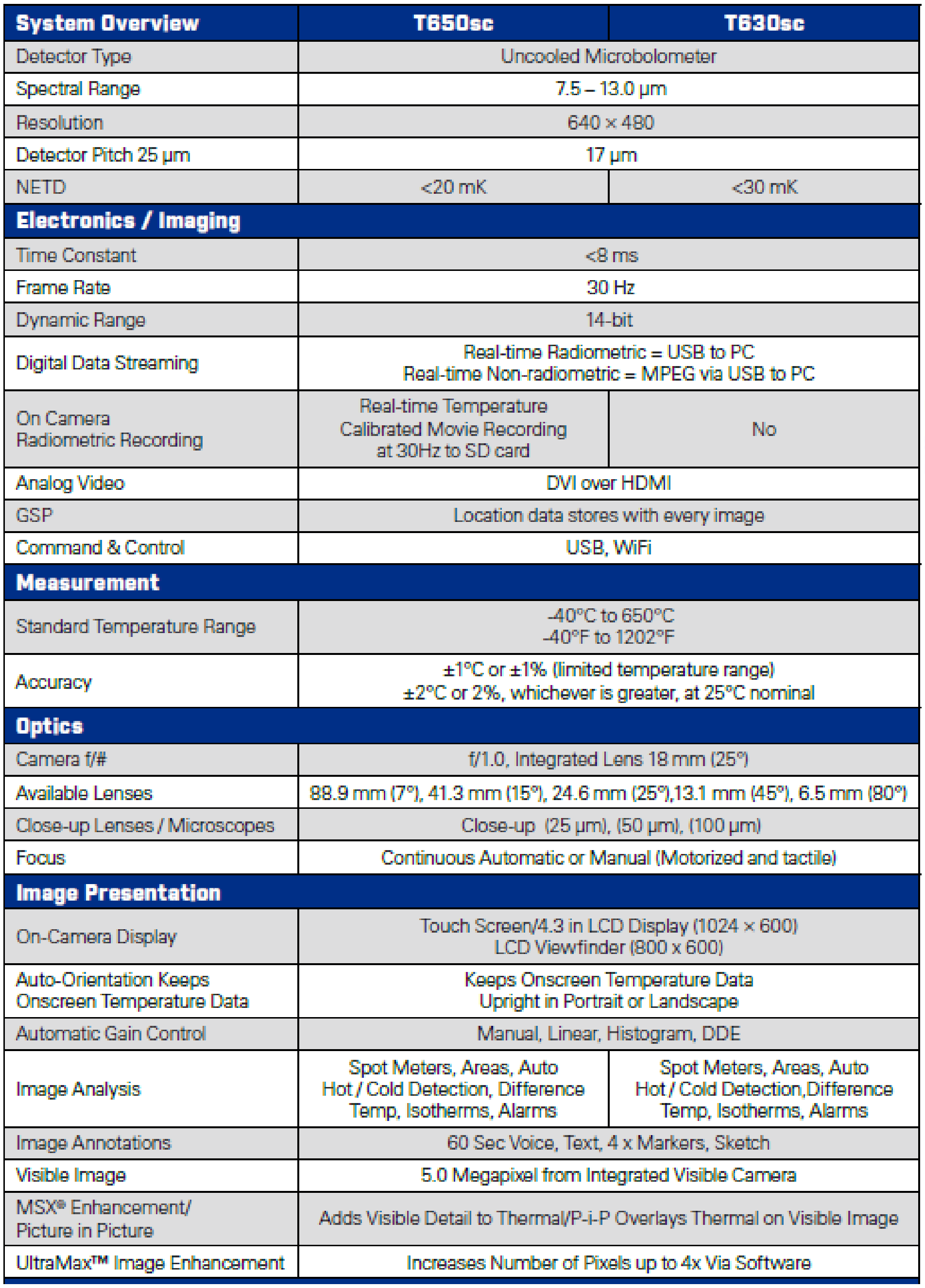
Image presentation modes	
Infrared image	Yes
Visual image	Yes
MSX	Yes
Gallery	Yes

Measurement	
Object temperature range	–10°C to +150°C (14 to 302°F)
Accuracy	±2°C (±3.6°F) or 2%, whichever is greater, at 25°C (77°F) nominal.

Measurement analysis	
Spotmeter	On/off
Emissivity correction	Yes; matt/semi-matt/semi-glossy + custom value
Measurements correction	• Emissivity • Reflected apparent temperature

Source: http://www.flir.com/uploadedFiles/Instruments/Products/C2/C2_Datasheet.pdf

Appendix A 2. FLIR C2 specifications.



System Overview	T650sc	T630sc
Detector Type	Uncooled Microbolometer	
Spectral Range	7.5 – 13.0 µm	
Resolution	640 × 480	
Detector Pitch 25 µm	17 µm	
NETD	<20 mK	<30 mK
Electronics / Imaging		
Time Constant	<8 ms	
Frame Rate	30 Hz	
Dynamic Range	14-bit	
Digital Data Streaming	Real-time Radiometric = USB to PC Real-time Non-radiometric = MPEG via USB to PC	
On Camera Radiometric Recording	Real-time Temperature Calibrated Movie Recording at 30Hz to SD card	No
Analog Video	DVI over HDMI	
GSP	Location data stores with every image	
Command & Control	USB, WiFi	
Measurement		
Standard Temperature Range	-40°C to 650°C -40°F to 1202°F	
Accuracy	±1°C or ±1% (limited temperature range) ±2°C or 2%, whichever is greater, at 25°C nominal	
Optics		
Camera f/#	f/1.0, Integrated Lens 18 mm (25°)	
Available Lenses	88.9 mm (7°), 41.3 mm (15°), 24.6 mm (25°),13.1 mm (45°), 6.5 mm (80°)	
Close-up Lenses / Microscopes	Close-up (25 µm), (50 µm), (100 µm)	
Focus	Continuous Automatic or Manual (Motorized and tactile)	
Image Presentation		
On-Camera Display	Touch Screen/4.3 in LCD Display (1024 × 600) LCD Viewfinder (800 x 600)	
Auto-Orientation Keeps Onscreen Temperature Data	Keeps Onscreen Temperature Data Upright in Portrait or Landscape	
Automatic Gain Control	Manual, Linear, Histogram, DDE	
Image Analysis	Spot Meters, Areas, Auto Hot / Cold Detection, Difference Temp, Isotherms, Alarms	Spot Meters, Areas, Auto Hot / Cold Detection,Difference Temp, Isotherms, Alarms
Image Annotations	60 Sec Voice, Text, 4 x Markers, Sketch	
Visible Image	5.0 Megapixel from Integrated Visible Camera	
MSX® Enhancement/ Picture in Picture	Adds Visible Detail to Thermal/P-i-P Overlays Thermal on Visible Image	
UltraMax™ Image Enhancement	Increases Number of Pixels up to 4x Via Software	

Source: http://www.flirmedia.com/MMC/THG/Brochures/RND_061/RND_061_US.pdf

Appendix A 3. FLIR T650sc specifications.