IR—Rx for Electrical Checkups

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and Daniel Sinclair

Unlike rattlesnakes and some abyssal fish[1], humans cannot see infrared (IR) light. Enter the modern thermographic IR camera, which images the IR emissions of a target using intuitive color palettes that graphically reveal the temperatures on its surface. Temperature anomalies in an electrical circuit generally indicate a problem.

These days, an infrared (IR) camera is potentially the most useful test device in the electrical inspector's toolkit because is the only instrument that enables you to *see* incipient problems as hotspots so you can fix things before they fail. Table 1 lists typical electrical components that can be routinely inspected using an IR camera. Software programs are available that enable "post-processing" manipulation of IR images or even generating professional inspection reports at the click of a mouse.

Table 1. Typical IR electrical inspection targets

• Air blast circuits	• Bolted connections
• Breaker tanks	• Breakers
• Bus ducts/cable trays	• Bushings
• Cable	• Circuit breakers
• Connections	• Cooling pumps
• Coupling capacitors	• Current on grounding conductors
• Disconnects	• Electronic circuit boards
• Electrical panels	• Faulty components
• Friction connections	• Fuses
• Generator brushes	• Heating elements
• Insulators	• Junction boxes
• Load tap changers	• Loose connections
• Motor control centers	• Motor windings
• Oil-filled transformers	• Phase (load) imbalances
• Radiators	• Splices
• Substations	• Switches
• Transformers	• Wiring

[1] Rattlesnakes and other pit vipers use their eyes to see during the day. But in the dark they use infrared sensory organs to detect and hunt warm-blooded prey. These organs are cuplike retina structures that are sensitive to heat and convey data interpreted as images by the animal's brain as infrared radiation hits them. The abyssal Black Dragon Fish (family: Malacosteid) can also see infrared light. Its long and transparent body is covered with photophores; it sports small eyes on long stalks, and has numerous sharp teeth.

TABLE 2. Some advantages of IR thermography
• Measure temperatures without contact
• Inspect equipment under normal load
• Nondestructive testing method
• Inspect with minimal disassembly
• Detect incipient problems
• Document problems for corrective action
• Minimize disturbance to operations
• Produce diagnostic images for written reports
• Send images via e-mail
• Record and/or output infrared in full-motion video clip
• Create reports of inspection results
• Verify new equipment installations
• Validate repair work
• Quantify lower risks for insurance auditors
• Maximize equipment life
• Avert unscheduled shutdowns
• Make timely repairs
• Reduce costs of component replacement and/or repair
• Prevent fires
• Improve safety
• Improve reliability

Camera or temperature gun?

IR cameras suitable for electrical inspections are expensive. Why not just buy a noncontact temperature gun? True, temperature guns are significantly cheaper than IR cameras. But you get what you pay for (see Table 2). Here are a few words of guidance.

Get training and read the WHOLE manual, no matter which device you choose. These instruments are still just tools of the trade, dangerous in untrained hands.

You can buy a temperature gun for only a few hundred dollars, but it will provide only one indeterminate point of measurement, generally output as a temperature reading on an LCD screen. You're never sure where the point is located, or if the reading is being compromised by reflections or background clutter.

In comparison, typical IR cameras provide an integrated, intuitive thermal image that enables you to see *exactly* where the problems are. Remember, the whole point of an electrical inspection is to quickly and precisely pinpoint problems. See how the IR image in Figure 2 precisely reveals a problem in a fuse block. Now imagine trying to extract similar precision from a single-point of electrical measurement. For electrical inspection, it's no contest. Go for a camera.

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Selecting an infrared camera

About the size of handheld digital video cameras and about as easy to operate, today's IR cameras are the killer solution for fast and accurate nondestructive electrical inspections. Unlike the large, cumbersome, and prohibitively expensive IR imaging systems of only a decade ago, today's IR cameras are lightweight, portable, and easy to use.

In the past decade, various technological advances have greatly advanced the state of IR thermography. Primary among these advances is the development of a type of detector called a *microbolometer,* a solid-state sensor consisting of thousands of individual elements that convert incipient IR into electrical signals. State-of-the-art microbolometer-equipped IR cameras operate at room temperature and are ideal for field inspections. They do not require cryogenic cooling, have relatively long battery life, and are ready to operate seconds after being turned on. Other advances include sophisticated, miniaturized, and efficient electronic hardware and "firmware" that interpret sensor output, and convert and display the data as intuitive images on an LCD monitor screen.

Maximize your IR camera investment by specifying a unit that meets all of your fundamental requirements. When considering a capital expense of this magnitude, it is prudent and highly recommended to try before you buy on actual targets under typical environmental conditions. Some helpful diagnostic questions and answers follow.

How much accuracy (often called "resolution") do you need? Lower priced cameras selling for about $10,000 to $15,000 will probably include a detector array containing 120 x 160 pixels; spend more than about $15,000 and you can get higher-resolution imaging from a camera with a detector array of 320 x 240 pixels.[2] Larger detector arrays are likely to provide higher-resolution imaging, but resolution also depends on the quality of the electronics and the lens.

Will you want to record both IR and visual images as "IR-visual" image pairs to facilitate identification of targets later on (see Figure 2)? You can carry separate IR and visible light cameras to do this. However, a line of cameras from one manufacturer includes both IR and digital capabilities, which enables you to take IR-visible image pairs from the same perspective.

How many images will you have to "scan" and save during an inspection tour? Don't even consider a camera that doesn't have built-in RAM and also a slot for removable memory media, such as CompactFlash®. A memory chip facilitates downloading speed and more important, enables you to carry extra media for extended field inspection tours. Conversely, if you forget to take a memory chip with you, you can still get some work done using the built-in RAM alone.

[2] A 160 x 120 pixel detector, contrary to some manufacturers' claims, does not actually provide 19,000 points of measurement. Camera electronics average the signal from individual neighboring pixels and require a minimum area of 3 x 3 = 9 pixels to provide a roughly 90% accurate temperature reading of a target spot. This resolution is reflected in the image output by the camera. Thus, a 160 x 120 detector actually provides about 19,000 ÷ 9 = 2,100 points, and 320 x 240 pixel detectors provide 76,000 ÷ 9 = 8,500 points of reasonably accurate, discrete measurement. See "Spot size" section later in this article for further information.

Do you have to scan a range of targets that include some within a few feet and others many tens of feet away? If so, be sure to specify a camera system that supports interchangeable lenses.

Will you be away from an AC source for an extended period? If so, you'll want a camera system that supports spare batteries and/or a 12-volt charging system that works in a vehicle.

What environmental conditions do you work under? If you have to work outside, be sure to specify a camera that is sealed and resistant to the incursion of water. Similarly, unless your work will be limited to laboratory environments, select a camera that carries a certification for resistance to damage from shock and vibration.

Do you think viewing your target in real-time on a large monitor could be useful to your work? If so, specify a camera that offers video recording and/or real-time industry-standard video output.

Can special features and accessories enhance your efficiency? For example, one manufacturer includes a built-in bright red laser target designator on their cameras, which places a dot at the center of the viewing field. The dot really helps aim the camera at night or under dark viewing conditions. Better cameras include an assortment of user-selectable color palettes as well as black-and-white to provide different ways to represent different temperature values. One camera line offers a small, intense, solid-state light to brighten dark targets for its on-board visible light digital camera. In addition, some advanced cameras can produce infrared full-motion video. You can also opt for a miniature Heads-Up-Display (HUD) that mounts on the frame of a pair of safety eyeglasses and is claimed by its maker to enhance situational awareness.

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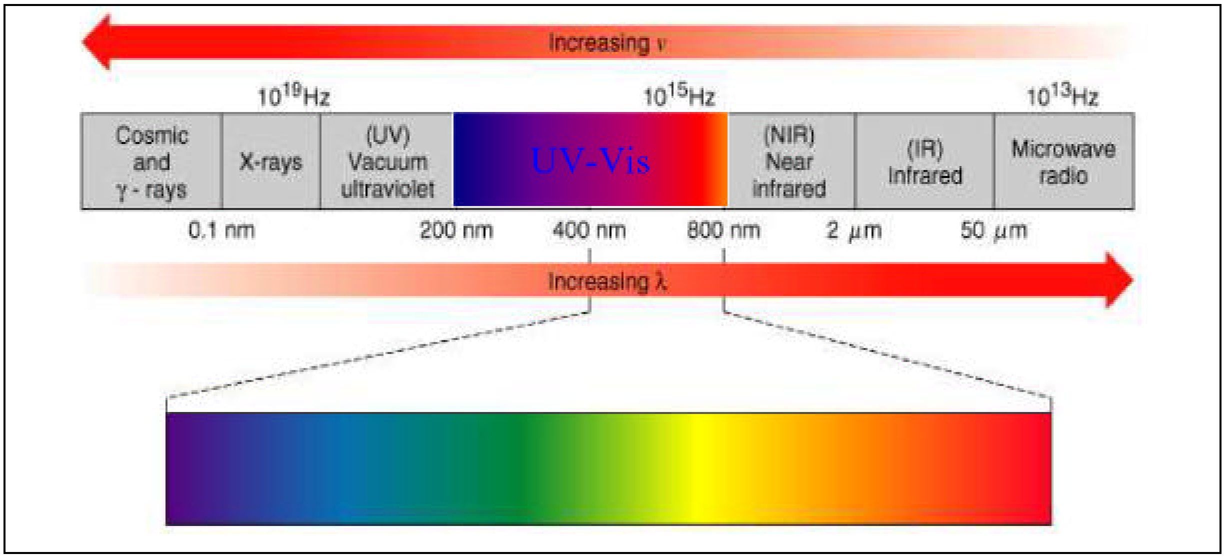


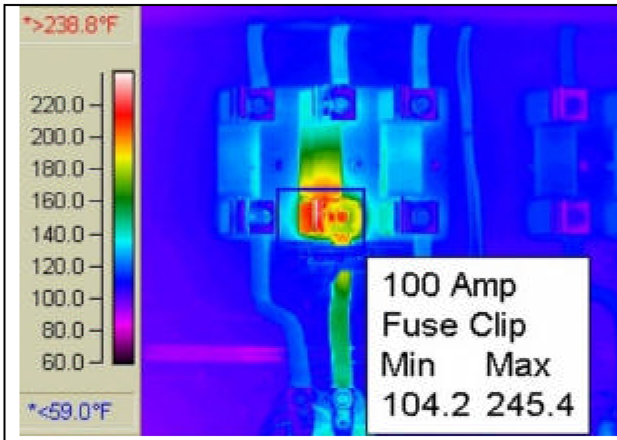
Figure 1. The infrared portion of the electromagnetic spectrum useful to electrical inspection includes wavelengths (denoted by Greek letter lambda, ?) from 2.5 to approximately 15 micrometers (µm). The infrared spectrum is in turn divided by convention into three main bands by wavelength : 1-2.5 µm (short-wave or SWIR), 3-5 µm (medium-wave or MWIR) and 8-12 µm (long-wave or LWIR). Today's state-of-the-art infrared cameras used for electrical inspection and other typical maintenance applications use an uncooled microbolometer focal plane array (FPA) and can see in the spectral range of 7.5 to 13 µm.

Infrared light reveals heat

The hotter a target, the more energy it emits in the infrared portion of the electromagnetic spectrum (see Figure 1). For electrical components such as resistors, resistance heating elements, motors, or transformers, which normally produce heat as a byproduct of their operation, warm IR signatures may be perfectly normal. However, for the preponderance of connective wires, fuses, splices, disconnects, and terminals, the production of excessive heat or the lack of heat where expected can indicate a problem. A low temperature could indicate an open circuit. Table 3 summarizes rule-of-thumb data from the International Electrical Testing Association (NETA) for preliminary indication of possible deficiencies based on anomalously high temperatures. Note that these deficiencies are evaluated on the bases of comparison to both ambient temperature and to identical components under the same load.

Basics

The use of infrared thermography to find electrical faults is a well-accepted practice among electricians and inspectors. The basic concept is that faulty connections and components in an energized circuit operating at or near rated load will heat up before they fail.



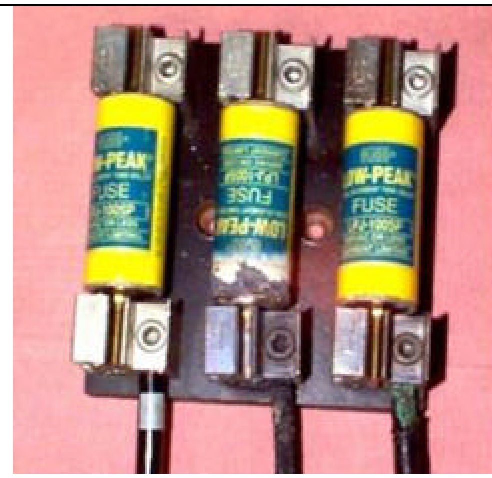


Figure 2. *(Left)* Thermal image of a fuse block in a live circuit shows that the lower terminal of the center 100A fuse is anomalously hot. *(Right)* After the assembly has been removed from the buss duct, the burned condition of the central fuse bottom terminal and wire is evident. The cause was a loose connection due to a broken spring clip. Corrosion can also be seen on the wire going to the bottom terminal of the right-hand fuse.

Thermographers often use devices to place a normal load on wall outlets. In a typical home inspection, for example, each branch circuit needs to be loaded at the last device in that circuit. One of the authors uses a pump powered with a 1 1/2 hp electric motor that pulls 13 amps. It will fire up problems immediately on both 15 & 20 amp circuits. (Consider that a similar load will occur at the bride's house when all the bridesmaids in every room are using curling irons & 1600 watt hair driers!)

Table 3. NETA guidelines for problem evaluation on the basis of ambient temperature and temperature of similar component under same load.

Temperature measured	**Indication**
1°C to 10°C above ambient AND 1°C to 3°C above similar	Possible deficiency
11°C to 20°C above ambient AND 4°C to 15°C above similar	Probable deficiency
21°C to 40°C above ambient AND > 15°C above similar	Deficiency
> 40°C above ambient AND > 15°C above similar	Major deficiency

*Data: NETA

The thermographer then scans all the devices and wires in the circuit from one end to the other, paying particular attention to each point of connection. This approach requires mapping out the physical location of each run throughout the facility or home and systematically and directly imaging each device. This procedure is well worth the effort if a problem is found and repaired before failure or fire occurs!

Common problems include oxidized fuses, loose or corroded (or missing) compression fittings or wire nuts, botched splices, etc. More times than not problems occur after a homeowner or electrically inclined neighbor replaces a duplex receptacle without using pigtails to connect the device. Instead they insert the building wire under the screws on the side of the duplex socket, one wire under each screw, thereby using the little breakoff tab between the two screws as a fuse link. Sooner or later the tab will burn out—but not before presenting an instantly detectable IR heat signature.

Buyers of new homes can enlist the services of a qualified thermographer to help certify the integrity for the new home against fire loss from mistakes made during construction. Loose connections in a breaker box, a heating system, or a hot water heater can be seen immediately when the circuit is under normal load.

Caveats

As with other testing methods, there are some caveats to consider before heading out on an inspection tour with an IR camera. An absolute requirement is that the operator must be trained and certified to at least Level 1 Thermographer (Level 2 or 3 are progressively superior certifications) by a bonafide training organization.[3]

Here are a few fundamental concepts for untrained yahoos.

Emissivity. While all objects above absolute zero[4] emit heat and infrared light, different materials emit infrared at different rates. This property is called *emissivity.* The range of emissivity runs from 0 (zero) for no emissivity to 1 (one) for a perfect IR emitter, which is termed a “black body” by physicists.

Be aware that polished metals, so common in electrical circuits and components, have poor emissivity, compared with the same metals having rough, dirty, or oxidized surfaces. The practical consequence of this is that a shiny copper wire, for example, will appear cooler than an oxidized copper wire when both are at the same temperature in the same infrared image. (For you Harley-Davidson® riders, another consequence is that mirror-polished cylinder and cylinder head fins on a motorcycle engine have low emissivity and are far less efficient at dumping heat into the air than black-finished fins.)

The thermographer learns to compensate for emissivity differences by training and with experience. Another common trap that many neophytes fall into is “finding” a problem that actually doesn’t exist or missing a problem that does in fact exist. For example, polished metal surfaces can reflect infrared radiation, and in some circumstances such reflections can be misinterpreted as hot spots on the target surface itself, while the shiny target itself may also be hotter than it appears to be because of its low emissivity.

Accuracy. Beyond making good common sense, accurate temperature readings are vital if you want to track and trend temperature changes over time. Such studies are the foundation of predictive maintenance practice, which is to project the time to failure of electrical and mechanical targets. A sequence of temperature measurements taken over time can reveal the rate of increase in temperature. This knowledge enables the inspector to predict when the target will reach a state that could compromise component reliability or plant safety and to recommend and schedule maintenance when convenient with regard to ongoing operations.

An important consideration is that changes in ambient temperature can affect a camera’s measurement accuracy. Better IR cameras have internal ambient temperature compensation systems including sensors and feedback circuits that automatically adjust for ambient variations.

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[3] Thermography training programs such as those offered by the FLIR Infrared Training Center (www.infraredtraining.com) and Snell Infrared (www.snellinfrared.com) provide hands-on instruction through sequential levels of certification, from basic Level 1 through expert Level 3, as well as special training for thermographers working with electrical inspections, building inspections, in research and development, and in other specialized applications.

[4] Absolute zero is the theoretical temperature at which substances possess no thermal energy, equal to -273.15°C, or -459.67°F.

Don’t trust a camera manufacturer’s accuracy specification that is limited to one temperature. The accuracy spec should apply over a temperature range that is at least as wide as the field conditions you expect. To retain its accuracy, an IR camera should be recalibrated by the manufacturer or a certified service on an annual basis or according to the manufacturer’s recommendation.

Direct vs. indirect measurement. An infrared camera sees only the *surface* of the target. As a result, wiring or components that are enclosed in a duct or are otherwise hidden from the camera by a wall or partition are invisible to the camera. A fault that produces heat in such wiring must be conveyed by convection of the air between the fault and the duct to the *surface of the duct itself*—a very inefficient transmission process.

The experienced thermographer knows that a rise of only a few degrees in the temperature of the surface of a buss duct, wall, or partition can indicate a major problem with hidden electrical components or wiring. Small thermal anomalies detected by indirect measurement can mask very serious situations, and in all cases should be followed up by direct measurement as quickly as possible by removal of access covers or other means.

Figure 3 details the results of an indirect thermal anomaly detected during an IR predictive maintenance inspection of the 480-volt distribution systems in the General Motors Powertrain Plant in Romulus, Michigan. The inspection revealed an abnormal heating signature at the connection of the isolation switch to the feeder buss that powers the east end of the V-8 block assembly line. Further IR examination, visual inspection, and torque tests confirmed that the affected joint should be disassembled and repaired. After cleaning the buss bars, the buss assembly was reassembled with a new compression bolt, washers, and insulators and put back into service without incident. If the situation had not been resolved, it would have become increasingly worse and could have led to a potentially explosive failure.

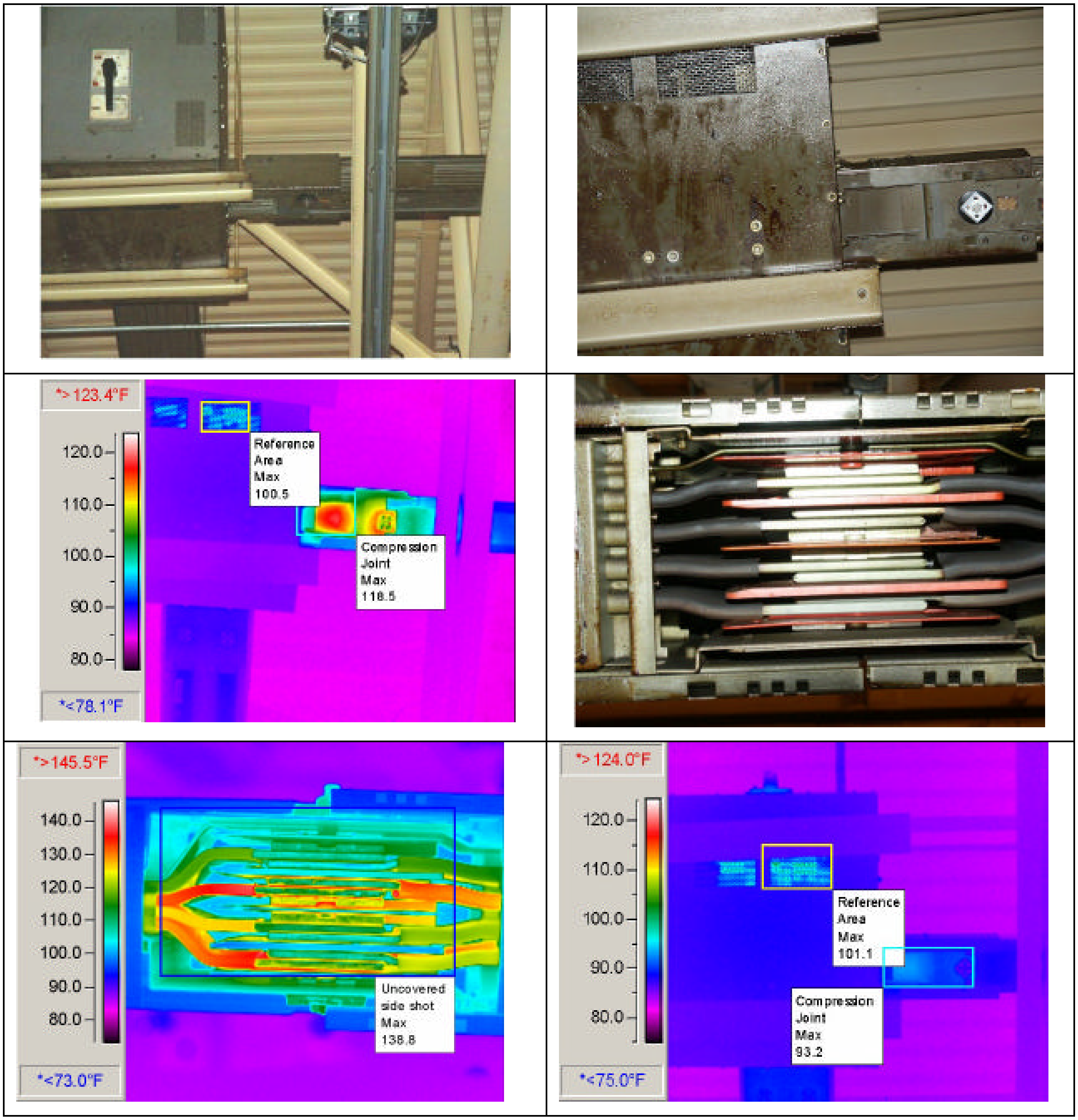

Figure 3. Results of a predictive maintenance inspection of the 480-volt distribution systems in the General Motors Powertrain Plant in Romulus, Michigan. **Top left:** Visual photo looking upward toward the ceiling showing buss duct from oblique angle. **Top right:** Closer view normal to buss duct shows the compression bolt assembly (square white object). **Middle left:** Thermogram of the surface of the reference area and compression joint reveals a surface temperature at the compression joint of 118.5°F. **Middle right:** Visual photo shows the compression joint after removal of access panel. **Bottom left:** Thermograph of the wiring shows hot spots as high as 138.8°F due to loose, dirty, and burned contact surfaces. **Bottom right:** Thermogram taken after the repair shows external duct temperature at the compression joint of only 93.2°F, a drop of 25.3°F.

Spot size ratio

Will you be measuring small targets that are far away from you, large targets that are close by, or a combination of situations? The concept of spot size—the smallest target area that an IR camera can accurately image and measure from a particular distance—is critical to accurate temperature measurement.

The problem is familiar to conventional photographers: the farther the camera is from a target, the smaller the target appears and the more challenging it is to capture with a high resolution image. With an IR thermography camera, the term *resolution* applies to both image quality and temperature accuracy.

The camera optics project the target image in their field of view onto the solid-state microbolometer detector chip, which is positioned precisely at the focal plane of an IR camera. This chip, which is often called a *focal plane array* or FPA, is divided into an array of discrete picture elements, or *pixels*, similar to the photosensitive pixels on the detector of a digital photographic camera. Each pixel on the FPA detector reacts to the incident IR light by changing its electrical state. This change is interpreted by the camera's processing electronics as a temperature value, and integrated with the temperature values from all the other pixels on the FPA. The resulting data may be output as an image on a viewing screen and/or stored in memory. To aid interpretation of the image, the firmware represents different regimes of temperature with different colors. Some cameras enable the operator to select different color palettes to optimize intuitive recognition of the thermal patterns in the image.

The reality is that it takes more than one pixel of data to provide thermal measurement accuracy approaching 90%. In fact, an image must impinge on at least a 3 x 3 pixel area, a total area of at least 9 contiguous pixels on the FPA. The bigger the target spot, the more accurately its temperature can be resolved. If a target "spot" covers less than 9 contiguous pixels, the camera's electronics will average the extraneous information into the temperature calculation, which will compromise accuracy. A common example is a cold sky behind a small hot spot on a distant electricity transmission tower. In this case, the indicated temperature is likely to be much lower than the actual temperature of the hot spot itself.

The ratio of the maximum distance at which a camera can accurately resolve and measure a minimum target spot size to the actual size of the target is called the camera's maximum *distance-to-spot size ratio* or simply its *spot-size ratio*. The solution to better resolution of distant small objects for IR cameras is the same as for photographic cameras—interchangeable telescopic lenses (zoom lenses are not available for IR cameras). Similarly, a wide-angle lens is needed to focus on nearby objects or to survey large areas quickly. As a result, a camera that supports a family of interchangeable lenses may be used to inspect an electrical connection on a utility pole 50 ft away or a fuse only 12 inches away.

Safety is paramount

Infrared inspection of electrical components can only be performed when the component or wire is carrying a normal load. Excess heat in the circuit can indicate problems (see Table 3). The process is inherently dangerous because all live circuits and components are potentially hazardous. Safety must be a paramount consideration during inspections and involves maintaining safe distances from live targets and the use of proper PPE (personal protective equipment).

In all cases, the thermographer must use the proper PPE such as approved shirt, pants, eye protection, and gloves as well as nonconductive tools when working near live circuits. Table 4 indicates the closest that qualified operators should approach live AC targets, based on voltages that may be present in the vicinity of most buildings. Table 5 summarizes typical effects that different levels of AC current have on the human body.

Table 4. Approach distance from AC equipment for qualified operators (air gap)*

AC voltage	Minimum approach distance
300V or less	Avoid contact
> 300V but < 750V	30.5 cm (1 foot)
> 750V but < 2kV	46 cm (1.5 feet)
> 2kV but < 15 kV	61 cm (2 feet)
> 15kV but < 37 kV	92 cm (3 feet)
> 37 kV but < 87.5 kV	107 cm (3.5 feet)
> 87.5 kV but < 121kV	122 cm (4 feet)
> 121kV but < 140kV	137 cm (4.5 feet)

*Source: FLIR Infrared Training Center

Table 5. Effects of different levels of AC and DC electric current on the human body*

Subject's perceived feeling	Direct current (mA)		Alternating Current (mA)				Physiological trauma level
			60 Hz		10,000 Hz		
	150 lbs body weight	115 lbs body weight	150 lbs body weight	115 lbs body weight	150 lbs body weight	115 lbs body weight	
Slight sensation	1	0.6	0.4	0.3	7	5	none
Perception threshold	5.2	3.5	1.1	0.7	12	8	none
Shock, not painful	9	6	1.8	1.2	17	11	none
Painful shock	62	41	9	6	55	37	Spasm, indirect injury
Muscle clamps source	76	51	16	10.5	75	50	Possibly fatal
Respiratory arrest	170	109	30	19	180	95	Frequently fatal
= 3/100 second of ventricular fibrillation	1300	870	1000	670	1100	740	Probably fatal
= 3/100 second of vent. fibril.	500	370	100	67	500	340	Probably fatal
= 5/100 second of vent. fibril.	375	250	75	50	375	250	Probably fatal
Cardiac arrest	--	--	4000	4000	--	--	Possibly fatal
Organs burn	--	--	5000	5000	--	--	Fatal if a vital organ

*Source: FLIR Infrared Training Center

Arc flash

As shown in Table 5, ordinary 60 Hz household current can be dangerous even at single-digit milliampere loads. Shock and arc flash or arc faulting can occur without warning and with explosive, deadly effect. In extreme cases, a circuit or component carrying a high level of electrical energy that is inadvertently grounded can cause a sudden release of explosive energy and generate temperatures hotter than that of the sun!

Standards NFPA 70E and IEEE 1584 provide safety guidelines to all personnel working on live electrical equipment, including thermographers. *Always assume that the target is hazardous and always utilize adequate and appropriate PPE and procedures.*

Sight glass inspection windows

The use of inspection sight glass windows made of crystalline material transparent to infrared light can greatly reduce the hazard of performing IR inspections of electrical cabinets and boxes (unfortunately, glass and ordinary plastics are opaque to long wave IR). To facilitate inspections and maintain safety, some industrial and commercial businesses are installing IR-transparent crystalline sight glass assemblies in the doors and panels of high voltage/amperage cabinets such as MCCs (motor control centers) and breaker boxes. After a sight glass window is installed, the thermographer can inspect the interior of the cabinet by simply aiming the camera through the sight glass. Without inspection windows, panels and doors must be removed from electrical cabinets by a qualified electrician to allow the thermographer to scan inside. However, removing the shielding exposes the thermographer and all personnel in the area to the then unshielded electrical hazard.

PostDisaster Cause and Origin Investigations

To a building owner or an insurance company involved in a property damage settlement, clear infrared images of normally invisible diagnostic evidence can be invaluable for planning the restoration effort and rationalizing settlements. The availability of authoritative thermographic records can reduce the need for insurance representatives to make onsite inspections, and the thermographic record of the repair or remediation can protect against future frivolous claims.

After fires, IR cameras can quickly locate remnant hot spots, providing potentially valuable data for insurance companies' Cause and Origin investigations. At minimum, an IR survey can help assure that a fire is truly extinguished; at best, it can suggest a point of origin.

Summary

Electrical circuits and components under normal load can be inspected for anomalies using a long wave infrared camera. The inspection of live electrical circuits carries inherent risks, and should be carried out with regard to all appropriate safety procedures.

The surface of connections and components that are hotter than expected can be detected with the camera, and loose, corroded, or otherwise faulty connections and failing components can be revealed. Situations that require immediate attention can be identified.

IR thermography can also be used to facilitate *predictive maintenance*—the determination of when incipient failure will occur. Thermographs taken over known intervals of time enable trending of the rate at which the condition or performance of a circuit or component is declining on the basis of increasing temperature. By projection, the moment of failure can be predicted, often with enough accuracy to order replacement parts and to plan necessary repairs during planned downtime to minimize disruption of ongoing operations.

ABOUT THE AUTHORS

Leonard A. Phillips is a science journalist who has written articles covering a wide range of technical topics. Formerly senior writer for infrared applications at FLIR Systems, he has written many articles on the uses of IR cameras and served as an editor on the Proceedings of InfraMation, the world's largest infrared thermography user conference. He has also been a high school science teacher.

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