ELECTRIC POWER RESEARCH INSTITUTE

# TECHNOLOGY INSIGHTS

*A Report from EPRI's Innovation Scouts*

# THERMOGRAPHY FOR POWER INDUSTRY APPLICATIONS

### THE TECHNOLOGY

***Infrared (IR) thermography is a rapid, effective, and reliable method for the inspection and monitoring of a wide range of materials and processes. Innovations in thermal imaging technology are facilitating rapid adoption of low-cost IR cameras across diverse industries, as well as enabling advanced nondestructive evaluation applications.***

### THE VALUE

***Thermal imaging can detect problems in power generation and delivery system materials, components, and infrastructure. The advent of low-cost thermal cameras and advanced imaging systems promises to expand use of IR thermography for improving worker safety and informing operations and maintenance decisions.***

### EPRI'S FOCUS

***Building on field demonstrations evaluating the capabilities of low-cost cameras and state-of-the-art thermography systems at power industry sites, EPRI is advancing IR imaging technology for conducting inspections, detecting defects, and monitoring conditions in hydroelectric dam, wind turbine, transmission line, and other applications.***

## TECHNOLOGY OVERVIEW

Thermography is used to detect heat that is emitted by materials and structures to create useful images of temperatures and temperature distributions across a surface. Temperature and heat transfer data are typically observed and/or recorded using an infrared (IR), or thermal, camera. Using thermal images, the observer can rapidly obtain valuable information related to the condition of a material or process, its environment, some subsurface conditions, and many abnormalities.

Thermography has been successfully applied in a wide range of industries, including power generation, defense, aerospace, food processing, nondestructive evaluation (NDE), medicine, and many others [1-3]. In the past, most of these evaluations had to be carried out with high-precision thermal cameras costing anywhere from thousands of U.S. dollars to more than $100,000. Recently, advances in thermal sensors have brought about a revolution in building performance analysis and other mass markets by enabling commercial introduction of low-cost IR cameras that deliver real-time imaging.

To assess low-cost thermal cameras and higher-fidelity thermography systems for utility applications, EPRI has conducted passive field inspections of electrical equipment and structures at several hydroelectric dams, wind turbines, as well as research and development (R&D) focused on specific industry needs. Figure 1 illustrates imaging and defect detection for a concrete repair using an IR camera plugged into a smartphone. This brief introduces thermal imaging technology and highlights R&D focused on power industry inspection, monitoring, and NDE applications.

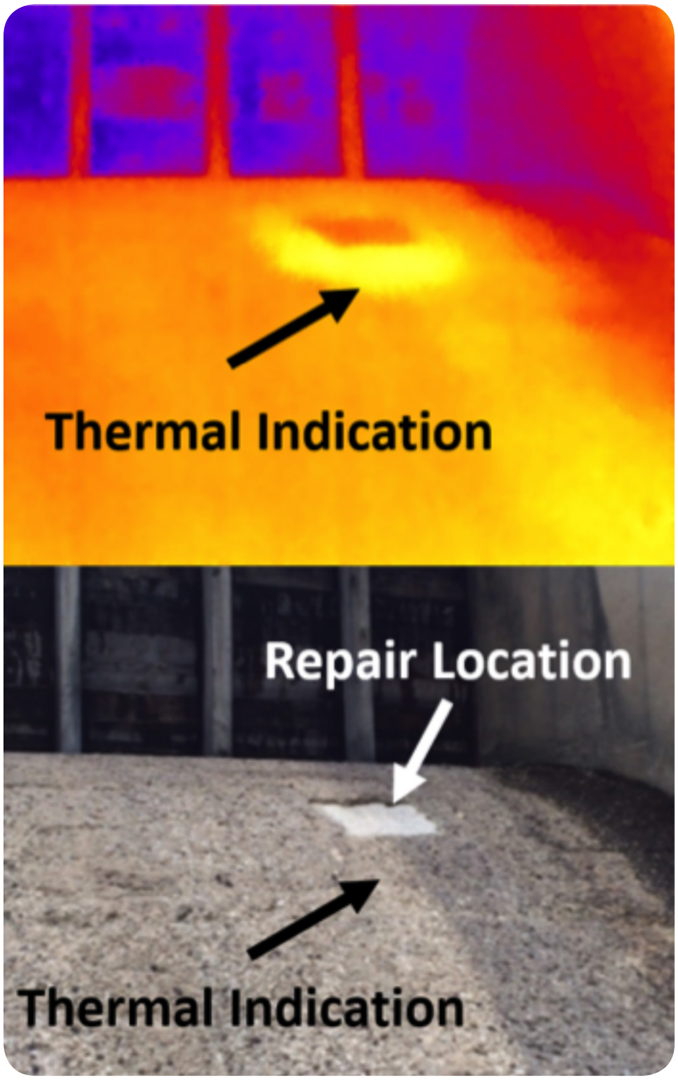


*Figure 1 – Indication of Potential Damage in a Concrete Structure*

## BASIC SCIENCE

All materials with a temperature above absolute zero (0 K, -273.15°C) emit electromagnetic radiation in the form of photons. Figure 2 shows the visible, IR, and other regions along the electromagnetic spectrum. The wavelength of emitted photons is dependent on the surface temperature of the material. For typical environments and temperatures encountered on Earth, photon emissions from surfaces are concentrated in the IR regime. As the temperature of a material increases, radiation increases in intensity and frequency (reduces in wavelength). This phenomenon is what causes materials to glow when heated to high temperatures—the increased energy of the photons causes their wavelength to enter the visible region of the electromagnetic spectrum.

Thermal imaging systems use special sensors to detect IR energy, then convert it into an electronic signal. They process the signal to produce a thermal image displaying temperature calculations, hot (and cold) spots, and heat distributions. They provide a non-contact approach for sensing temperature and imaging heat transfer. IR measurement accuracy is influenced by a number of factors related to application, target distance, surface emissivity, incident angle, environmental conditions, and IR camera selection (number of pixels, zoom, temperature sensitivity, wavelength range, etc.).

Emissivity refers to the thermal emission efficiency of a surface, ranging from 0 (no thermal emission) to 1 (perfect emitter). Generally, the higher the emissivity, the better the evaluation that can be performed using thermography. Shiny surfaces have an emissivity closer to 0, making them harder to evaluate. Dull, dark, charred, or lightly corroded/oxidized surfaces are often much easier to evaluate due to emissivities closer to 1. In the field, this means that components that have been in use—with rusty or dirty surfaces—are often easier to inspect than those that are new due to higher emissivities. A secondary advantage is that minimal or no cleaning may be needed to perform thermography, whereas other inspection and NDE methods may require preparation of the surface to be interrogated. Emissivity, as experienced by a thermal imaging camera, is influenced by angle of incidence with the surface, making sensor location an important consideration in field applications.

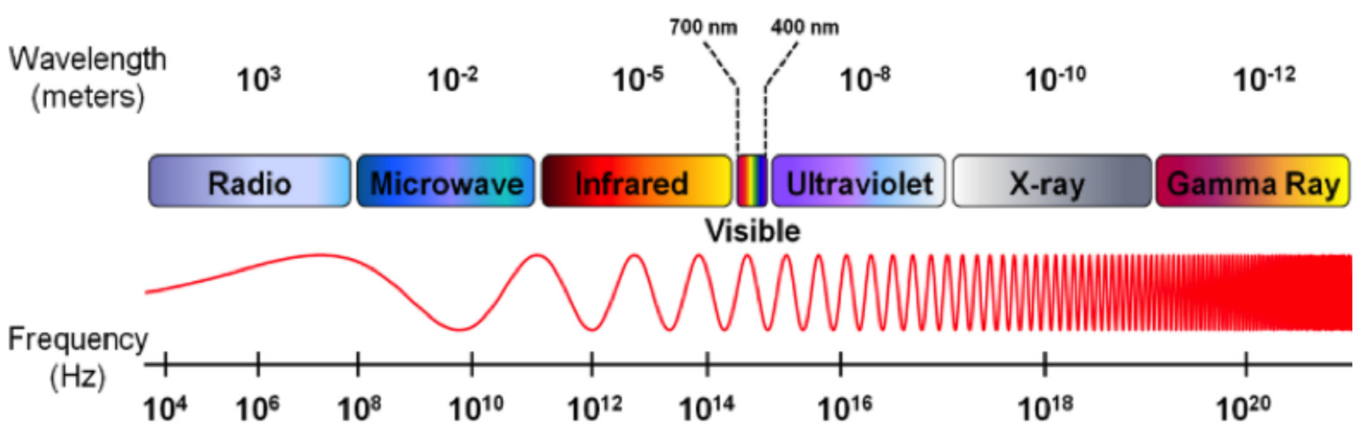


*Figure 2 – Spectrum of Electromagnetic Radiation*

Commercial IR cameras can capture still and video images in real time to rapidly perform evaluations over large areas, of many components, and at fine scales—and without the need for surface contact. In addition, thermal cameras of varying sizes, wavelength ranges, and costs can be employed to address specific needs. They provide simple, easy-to-understand output suitable for immediate inspection and monitoring applications and for computer-encoding and subsequent analysis. Defects can be identified and sized in a wide range of materials and settings. NDE can be performed passively, only using imaging, or actively, capturing images while applying a dedicated external energy source such as a heat pulse or vibration.

## VALUE TO THE INDUSTRY

Low-cost thermal imaging cameras are expected to allow economical condition assessment of many power industry structures, systems, and components. Despite having reduced sensitivity and lower pixel resolution than state-of-the-art thermography systems, they generate images of sufficient quality for a wide range of important tasks, including

- Measurement of temperature and heat distribution;
- Identification and sizing of defects in metal, composite, concrete, and other materials;
- Identification of overheating and aging electrical and mechanical equipment;
- Location of inadequate insulation or leaks in piping systems; and
- Monitoring of environmental conditions.

State-of-the-art IR imaging systems perform the tasks listed above but at a much higher resolution and thus with increased accuracy, an important consideration for safety-critical components and in high-value applications not amenable to conventional NDE techniques, such as inspection of hydroelectric dams and wind turbine blades. At a purchase price of only a few hundred dollars, low-cost IR cameras may well find widespread use at various types of power generation and delivery facilities that would not have previously been evaluated using thermography.

Since thermal imaging does not require contact with a surface, inspections can be performed from the ground level or from aerial platforms. Thermal imaging sensors also can be delivered to dangerous or inaccessible locations as payloads on robotic devices. These attributes not only expand inspection coverage, but also allow field evaluations to be conducted without exposing workers to potentially hazardous conditions.

## STATE OF THE TECHNOLOGY

In 2015, EPRI conducted screening studies at several hydroelectric power plants to assess low-cost IR cameras for rapid inspection and first-pass NDE of large concrete structures, electrical equipment, and other on-site infrastructure. These studies complement recent and continuing R&D addressing the development and use of advanced thermography techniques for power plant NDE, wind turbine blade, solar photovoltaic (PV) array, transmission line component, and substation applications.

Generally, EPRI's work indicates that off-the-shelf thermal imaging technology is ready now for a wide range of power industry settings, including real-time detection of some important defects and performance deficiencies. Moreover, purpose-built thermography systems have the potential to overcome technical and practical barriers to the inspection and NDE of certain structures and components. Sample uses and EPRI R&D activities are highlighted below (this is not a comprehensive list).

***Overheating/aging:*** Degraded components tend to generate additional heat relative to those that are operating properly or more efficiently. Thermography thus can be used to identify equipment that is overheating or beginning to age, such as electrical components, degraded mechanical bearings, etc. Figure 3 shows an image collected at a U.S. hydro plant showing two electrical relays, one that is older (indicated by the black arrow) and a newer one in the foreground (indicated by the white arrow). The older relay is beginning to age, causing it to heat up more than the newer relay as indicated by the much different heat signature shown in the figure.

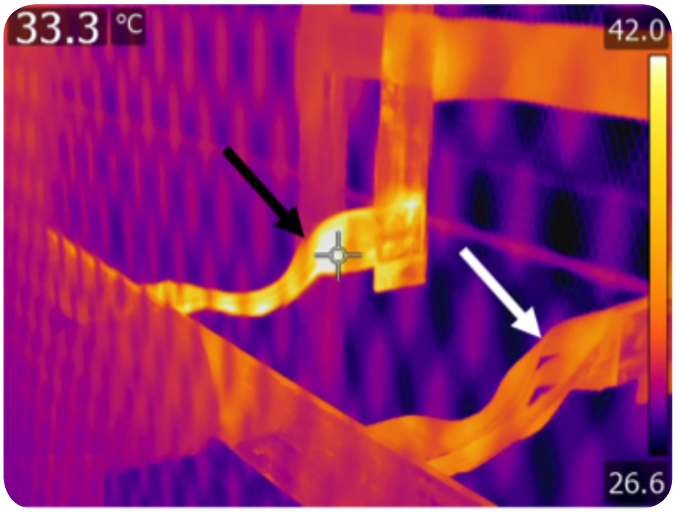


*Figure 3– Older, Warmer Electrical Relay (black arrow) and Newer, More Efficient Relay (white arrow)*

***Defect detection and sizing:*** Thermography can be used as a rapid screening tool to identify and size defects in a wide range of power plant materials and systems. Passive thermography and active NDE techniques such as flash thermography and vibrothermography can be applied effectively and have been demonstrated by EPRI in materials with very high thermal conductivities, such as aluminum and steel, as well as highly insulative materials, such as concrete [4-6]. Figure 4 shows an image from a flash thermography inspection, where a heat pulse is used as the external energy source. The technology proved capable of detecting hidden defects of varying sizes, shapes, and depths on the opposite surface of a stainless steel plate and in a lap weld. The inspection duration was only a few seconds. Traditional inspection methods for detecting comparable flaws over comparable areas could take 100 times longer while generating results that are more difficult to interpret.

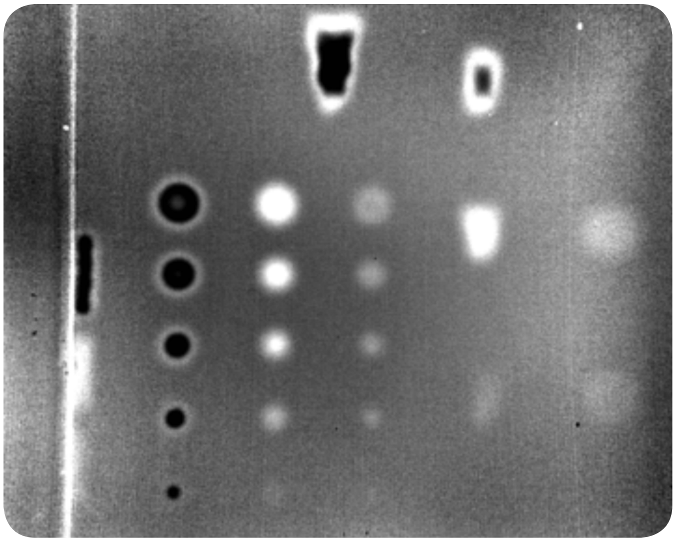

*Figure 4 – Flash Thermography Detection of Engineered Defects in Stainless Steel*

***Wind turbine blade inspection:*** Standard visual inspection of in-service blades requires turbine shutdown and can expose workers to safety risks. Thermography techniques underlie a ground-based inspection system being developed and demonstrated by EPRI for assessing the structural integrity of operating wind turbine blades [7,8]. Known as SABRETM, the system includes a specialized long-wave infrared (LWIR) camera with a fast-frame-integration time to detect the very slight IR emissions from structural anomalies. As blades rotate, operational loads and dynamic forces cause thermo-elastic and frictional heating from damaged blade material. In testing performed at wind projects in collaboration with Duke Energy and DTE Energy, sensitive thermographic sensors incorporated in a ground-based SABRETM prototype proved capable of detecting hot (and cold) spots, as shown in Figure 5. Rapid, safe inspections identified internal and external blade flaws without interrupting renewable energy production. Real-time images recorded for later defect characterization were applied to inform maintenance planning.

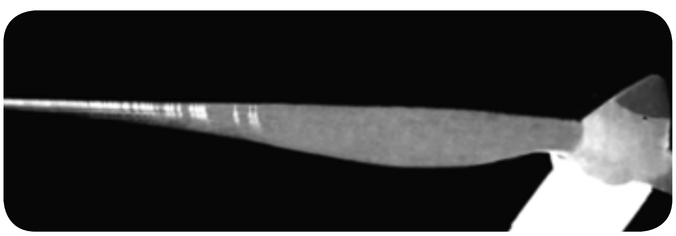

*Figure 5 – Wind Turbine Blade with Thermographic Hot Spots Revealing Internal Anomalies*

***PV plant inspection:*** Thermal imaging is capable of displaying temperature gradients and detecting hot and cool spots in PV modules due to manufacturing defects, cracked glass or cells, shading, soiling, defective bypass diodes, wiring failures, faulty interconnections, and other issues affecting solar energy production. Some of these problems may otherwise be undetectable. Figure 6 displays an aerial image of a large array, highlighting failures causing under-performance across numerous modules. The image shown in Figure 7, which illustrates indications of a failed bypass diode within an individual module, was applied in a successful warranty claim. EPRI has developed baseline guidance supporting use of IR cameras for PV inspection and diagnostics [9]. A recent EPRI study addresses the possible use of unmanned aerial vehicles, with payloads incorporating thermal sensors, to allow for frequent, low-cost inspection of large-scale PV arrays and accelerated identification of problems resulting in production losses [10].

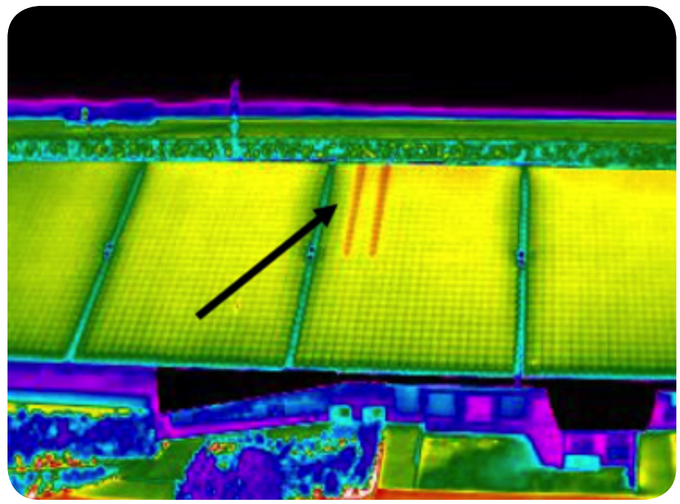

*Figure 6 – String Failures Evident as Hotspots in Infrared Image of 800-kilowatt PV Array (Credit: Oregon Infrared LLC)*

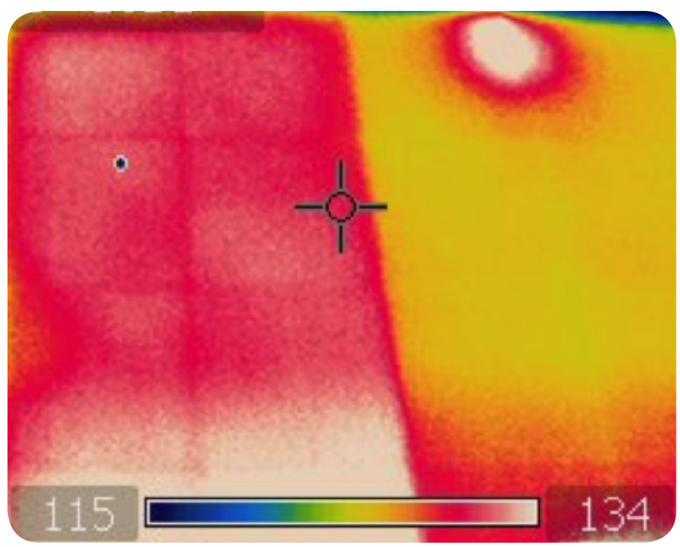


*Figure 7 – Excessive Heating in PV Module Substring and Junction Box Due to Bypass Diode Failure*

***Substation monitoring and diagnostics:*** IR cameras with online substation monitoring capability have existed for many years [11,12]. The challenge lies in intelligently processing the data in a way that improves the accuracy and confidence of the IR measurement and its interpretation, either by humans or through automated analysis. EPRI has worked on projects to derive algorithms that can correct, to a certain extent, factors that can influence IR measurement accuracy (Figure 8). One working prototype system was used for a proof-of-concept study to act as the primary system for developing IR algorithms using data from a component defect simulation test bed. A second IR correction system was tested and implemented to support online monitoring of component condition at a utility substation. IR cameras with intelligent data processing algorithms could automate 24/7/365 monitoring of the thermal condition of substation equipment and increase reliability by detecting impending failures before outage-causing events occur.


*Figure 8 – IR Measurements from an Online Substation Monitoring System, Corrected Using EPRI-Developed Algorithms*

***Overhead transmission inspection:*** IR imaging has been widely used to detect components that are not operating as designed in transmission systems [13]. Recent EPRI research [14,15,16] evaluated a number of different IR imaging technologies for assessing the condition of compression connectors, finding that thermography works well as a first-pass detection tool while reducing maintenance effort (Figure 9). The capability for non-contact measurement results in improved worker safety. Often, the right IR camera system can pay for itself by preventing just a single unwanted incident. Field experience shows that ambient conditions at the time of thermography, such as wind speed, precipitation, and temperature, can affect measurement accuracy.

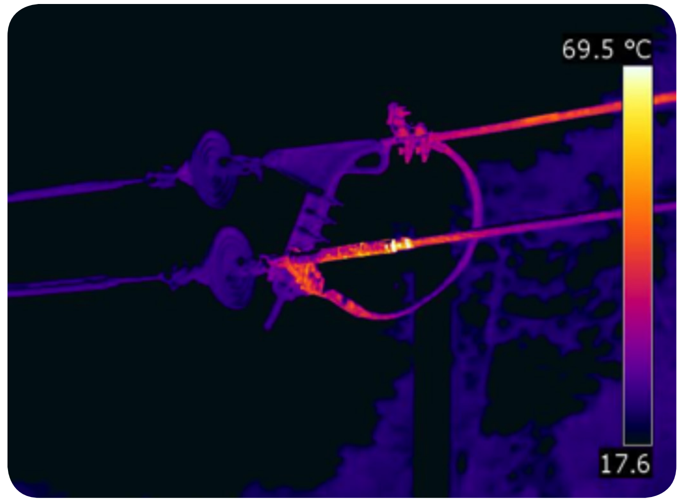


*Figure 9 – Infrared Measurement Showing Excessive Heating of a Compression Dead-End Connector*

## NEXT STEPS AND COLLABORATIVE OPPORTUNITIES

Thermal imaging technology is ready now for inspection, NDE, performance monitoring, and other applications across the power generation, transmission, and distribution sectors. Low-cost thermal sensors enable handheld IR cameras, fixed imaging systems, and robotic delivery modes. EPRI seeks to continue and expand collaborative R&D with energy providers to create advanced applications of thermography that help enhance the reliability, efficiency, and affordability of electricity and protect health, safety, and the environment.

In 2016, additional U.S. and international host sites are sought for demonstration and refinement of the SABRE™ wind turbine blade inspection system. EPRI also plans to test a prototype thermal imaging robot for inspecting the condition of dry cask storage systems housing used nuclear fuel rods.

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