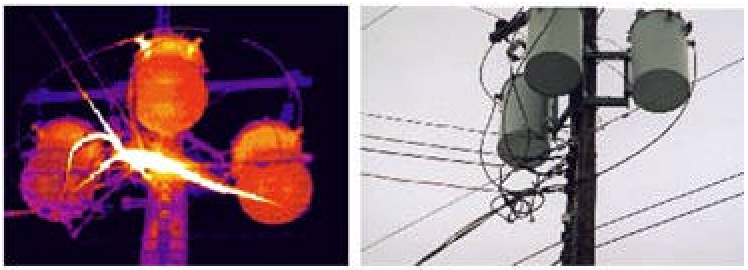
Improving Electrical System Reliability with Infrared Thermography

Source : http://www.infraredelectrical.com/index.html

Temperature and the resulting thermal behavior of electric power generation and distribution equipment and industrial electrical systems and processes are the most critical factors in the reliability of any operation or facility. Temperature is by far the most measured quantity in any industrial environment. For these reasons, monitoring the thermal operating condition of electrical and electromechanical equipment is considered to be key to increasing operational reliability.



Introduction

Infrared thermography (IR/T) as a condition monitoring technique is used to remotely gather thermal information for monitoring the condition of virtually all of the electrical components on an entire system and from generation to end user.

Why can we say all equipment? Because all equipment when operating under regular conditions, has a normal operating thermal signature which is typical of the specific component being inspected. Infrared thermography presents this normal signature or baseline to us.

Once the baseline is established, IR/T will reveal the thermal variances deviating from the norm. This localized thermal deviation can either be caused by an overheated condition or absence of heat. The information is reviewed and decisions are made for repair or to plot the temperature change over time and repair the component at a more opportune time. The information can be stored and fully analyzed at a later date providing complete computer aided predictive maintenance capabilities and trending.

Infrared Thermography is currently experiencing rapid growth as more and more electric utilities and industrial sectors are embracing the technology. The reason for this growth is company personnel understand the benefits of this non-contact, nondestructive method. The main benefit being, to find deteriorating components prior to catastrophic failure. Thermography provides another set of eyes allowing a whole new level of diagnostic aid and problem solving.

Infrared Thermography is simply a picture of heat, when you consider our natural environment, everything is radiating a particular intensity of thermal energy. Our eyes are unable to see this infrared energy unless the temperature of the object goes beyond 5000C. With an infrared imaging instrument the thermal energy surrounding us can be detected, imaged, measured and stored for analysis.

Infrared Condition Monitoring

Temperature is one of the first observable parameters that can indicate the condition of operating electrical equipment. Heat is a byproduct of all work whether is it electrical, mechanical or chemical. All industrial processes operate with mechanical, chemical and electrical energy being converted from one form to another. The natural byproduct of the conversion process is heat. Heat generated either intentionally or unintentionally is transferred, contained and otherwise being controlled to suit specific requirements. Thermal energy not in control will cause problems within any type of equipment whether electrical, mechanical or process related.

No electrical system is 100% efficient. Current flowing through an electrical system will generate a small amount of heat because of electrical resistance. With time the components and contact surfaces of the electrical system will begin to deteriorate. With the deterioration comes increased resistance and with resistance, increased heat. This course will continue until eventual failure. Fluctuating and high loads, vibration, metal fatigue, age and specific operational environments such as extreme ambient temperatures, wind, chemicals or dirt in the atmosphere will increase the speed of degradation and the number of faults in electrical systems.

Universally, the electric industry understands that temperature is an excellent indicator to the operating condition and hence the reliability and longevity of an electrical component. Associations like IEEE, ANSI, IEC and manufacturers all publish standards and temperature ratings for electrical components. It is well understood that the life of electrical components and materials is drastically reduced as temperatures are increased.

It is logical, then, that evaluating the thermal signature of electrical systems with Infrared Thermography will provide the maintenance department, from generation to the end user, with valuable information directly related to operational conditions of virtually every item through which electric current passes.

Infrared condition monitoring is the technique capable of revealing the presence of an anomaly by virtue of the thermal distribution profile that the defect produces on the surface of the component. The defect will normally alter the thermal signature of the surface due to the change in the amount of heat generated and the heat transfer properties of the component. To determine an adverse operating temperature of a component it is necessary to first determine a baseline. For electrical systems the baseline is established when the system is operating under normal load and operating conditions.

Once a clear understanding is obtained on what the normal thermal signature is for the many electrical apparatuses and components, the thermography technician will be able to quickly identify a thermal anomaly. On larger more critical components such as transformers, circuit breakers, capacitors etc., the baseline images and data will be stored and compared to new data collected from each inspection interval. It is the job of the thermographer to identify, record, analyze and diagnose indications of abnormal heat transfer in the electrical equipment or components.

It is important that the data collected is accurate, repeatable and is properly analyzed. This depends on many variables, the main being the thermographers level of understanding of infrared instrumentation, background theories and the level of field experience.

Electrical Thermography

The main application for thermography has always been, and still is electrical system inspections. Infrared thermography has been used as a condition monitoring tool to predictively maintain electrical systems, even before the terms "condition monitoring" and "predictive maintenance" were used. In 1965, the Swedish Power Board began inspecting approximately 150,000 components a year. In 1976, the UK Electrical Generation Board began utilizing infrared thermography for predictive maintenance on the transmission lines. Ontario Hydro and BC Hydro in Canada also became involved in infrared thermography during this time.

By the year 2000, virtually every electric generation and distribution company as well as every major manufacturing and process facility will be using infrared thermography as a condition monitoring technique to increase reliability and decrease downtime.

Why such an interest in electrical thermography? Simple. All electrical maintenance personnel know as soon as new electrical components are installed they begin to deteriorate. With fluctuating and continual loads, vibration, fatigue, age, and other things like operating environment, all of these will increase the probability of faults in electrical components. These faults, if not found and taken care of, will lead to catastrophic failures, unplanned shutdowns and losses of production.

Component	Rise above Ambient	Actual Temp.
Bus connections with unplated copper to copper connections	30 C	70 C
Connections to insulated cables silver plated	45 C	85 C
Class 90 insulation (THHN)	50 C	90 C
Circuit Breaker contacts, conducting joints etc.	85 C	125 C
Air switches - contacts- copper or copper alloy - conducting mechanical joints - copper	33 C 43 C	75 C 90 C

Benefits of Infrared Electrical Inspections

Since most problems on an electrical system are proceeded by a change in its thermal characteristics and temperature, whether hotter or cooler, a properly trained and experienced thermographer is able to identify and analyze these problems prior to costly failure occurring.

Infrared electrical inspections provide many benefits to the recipient. The two key advantages, from which the others stem, are:

1. The reduction in disassembling, rebuilding or repairing components which are in good operating condition. This type of repair is meaningless and costly and may lead to a 30 percent reduction of production. Furthermore, it is not guaranteed that the component will be in better condition after the repair, since the location of the problem or cause was not established. With infrared thermography you identify and hence repair only what needs repairing.

2. Problems that, truly exist will be identified quickly, giving time to repair the problem before failure. In most cases the problem is identified well before the problem becomes critical. Depending on the temperature and criticality of the component, the decision can be made to repair immediately, repair at the first opportune time, or monitor on a continual basis until the critical temperature is reached or until the repair can be scheduled. Identifying a true anomaly, scheduling the repair, and eliminating the actual cause of the problem within a proper time frame is the most efficient and cost effective way to maintain the system.

The other advantages of an infrared inspection program are based on the above overall advantages, yet are no less important. They are:

1. **Safety** - failure of electrical components could be catastrophic, injuring or even killing employees, maintenance personnel or the public.

2. **Greater System Security** - locate the problems prior to failure greatly reduces unscheduled outages, associated equipment damage and downtime.

3. **Increased Revenue** - with more uptime, revenue is maximized. With less maintenance on good components and faster repairs of faulty components, maintenance costs care are reduced leading to a better bottom line.

4. **Reduced Outage Costs** - the cost of an emergency outage is ten times greater than planned maintenance.

5. **More Efficient Inspections** - since all common electrical problems announce themselves as an increase in temperature, they are easily detected in a minimum amount of time. No service interruption is required for infrared inspections.

6. **Improved and Less Expensive Maintenance** -
    a. precise pinpointing of problems minimize time required for predictive and preventive maintenance,
    b. maintenance efforts directed to corrective measures rather than looking for the problem,
    c. repair only what requires repairing, reducing repair time and replacement of good components.

7. **Reduce Spare Parts Inventory** - with improved inspection techniques giving advanced warning of failure, fewer spare parts are required in inventory. What would it mean to the bottom line if your spare parts inventory could be reduced by 10%?

8. **Reduced Operational Costs** - with the system up and running for longer periods of time, the reduction and improvement of inspections, maintenance, spare parts inventory and outages will reduce the overall cost of operations.

In the first part of our article, we concentrated on what thermography is, how it works, and why electrical inspections are the main industrial application for infrared thermography. Whether you purchase an instrument, rent or hire an outside service company, the return on investment is amazingly fast. The benefits of establishing an infrared inspection program at most facilities far out weigh the investment, these are:

1. Safety
2. Greater system security
3. Increased revenue
4. Reduced outage costs
5. More efficient inspections
6. Improved and less expensive maintenance
7. Reduce spare parts inventory.
8. Reduced operational costs

Now we will look at the more practical side of infrared electrical inspections. We will discuss the sources of thermal patterns on electrical systems. Thermographers beware!! Not all "Hot Spots" are problems..... We will then look at a variety of uses and applications, return-on-investment and training.

Sources of Thermal Pattern Variances on Electrical System

Thermal energy generated from an electrical component is directly in proportion to the square of the current passing through it multiplied by the components resistance (I2R Loss). As the condition of the component deteriorates, its resistance can increase and generate more heat. Then as the component temperature rises the resistance increases further. This self propagating process continues until the melting point of the weakest component is reached. By utilizing thermography to inspect electrical systems and components under load the faulty components can be identified and classified by severity. It is interesting to note that because heat loss is proportional to the current, unbalanced or overload conditions can be identified. (I2R Loss)

When performing an infrared inspection of an electrical system it is important to realize that all of the radiation leaving a surface is not due solely to the temperature of the surface. Unless knowledge, understanding and caution are applied during the analysis portion of the inspection, documentation and interpretation may result in the false conclusion that a fault does or does not exist.

Thermal pattern variations are normally referred to in two ways:

1. **Real Temperature Differences** - These are thermal patterns caused only by infrared energy exiting the surface of the object.
2. **Apparent Temperature Differences** - they are patterns which are due to factors other than variations of the target surface.

The causes for thermal pattern variations from electrical components are:

Real	Apparent
I2R Loss -increased Resistance -load fluctuations	Emittance
Harmonics	Reflectance
Induced heating	Transmittance
Convection	Geometric Variations
Thermal capacitance	
Evaporation	

Of the real thermal pattern variations, only three will provide indications of a problem on an electrical system:

1. I2R Loss
2. Harmonics
3. Induced heating

The other three (convection, thermal capacitance, and evaporation) will make a true temperature change at the surface of the component, but it does not provide indication of an electrical fault. In fact, they may actually provide false information by disguising or reducing the amount thermal energy associated with the anomaly, or heat up a component and make it appear to be a fault.

All of the real and apparent causes of thermal pattern variations are very important to understand for anyone performing infrared inspections, especially electrical inspections! Remember, the actual component temperature may change or may not change. The thermal variations are not necessarily caused by the electrical components themselves but by outside forces creating the thermal variations, creating or disguising problems. Many people say it is easy to perform an infrared electrical inspection, be careful - it's easy to be fooled. Beware, IR electrical inspections are one of the most difficult applications if done properly, not just being a "hot spot" finder.

True Faults are Caused from

1) I^2R loss

The most common loss of power in an electric circuit is the heat produced when current flows through a resistance. The exact relationship between the three quantities of heat, current and resistance is given by the equation:

$P = I^2R$

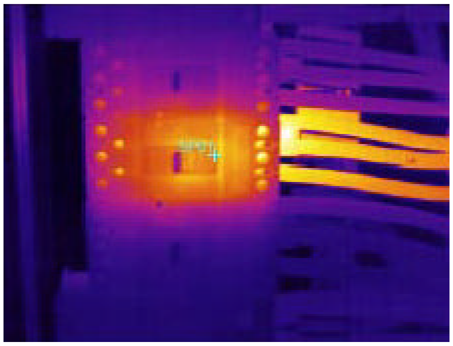
Where **P** = Power and is the rate of doing work or the rate at which heat is produced. It can see from the equation that the amount of thermal energy produced is increased or decreased by increasing or decreasing the current or resistance.

This I^2R heating, as it is often called, takes place in the circuit wires as well as in resistors. The basic unit of Power is the watt, wattage is equal to the voltage (E) across a circuit multiplied by current (I) through the circuit. Below we have divided the effects of power under two headings, since the reason for the power consumption provides an indication as to how the system or components are operating.

1a) Load

As the load increases in a circuit the power output will increase as a square of the load, and the temperature of the entire circuit and components on the circuit will increase. From a thermographic point of view, load is usually looked at as a specific type of problem with specific thermal indications. As the load on an electrical component rises, so does the temperature. An even load on each phase of a three phase system for example, should result in uniform temperature patterns on all three phases. An anomaly is identified when the overall component and conductor temperature is too high, indicating an overload condition. An unbalanced condition can also be a problem and is identified by the conductors not displaying a balanced or equal thermal pattern and temperature.

Unbalanced or overloaded components can be identified thermally because the temperature remains relatively constant along the conductor or component as long as the object size and mass remains the same.



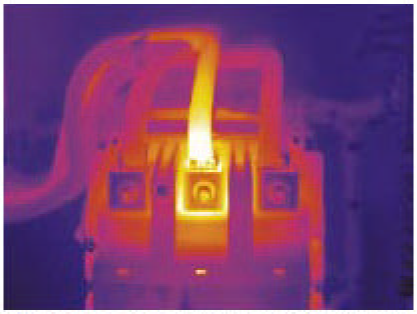
This Thermal image identifies a warm breaker. There is no problem with the breaker, there is just a load variation between the three breakers.

1b) Localized Resistance

Here we consider a resistor. A resistor in any component in the electric circuit, this can be connections, fuses, switches, breakers and so on. Under standard operating conditions each component will have a certain "normal" resistance associated with it. It is when the resistance deviates from this norm that the component begins to heat up and must be identified and repaired.

Overheating of components can have several origins. Low contact pressure may occur when assembling a connection or through wear of the material e.g. decreasing spring tension, worn threads or over tightened bolts. Another source could be deteriorated conductors of motor windings. As the component continues to deteriorate the temperature will continue to increase until the melting point of the material is reached and complete failure occurs.

This type of fault can generally be identified because there is a "hottest point" on the thermal image. What this means is, the heat being generated is greatest at the fault point with a tapering off of thermal energy away from the point of highest resistance.



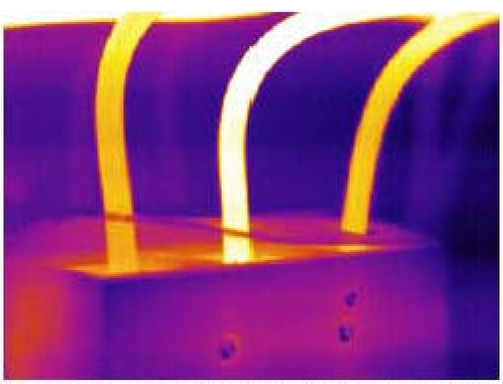
Increased resistance at the bolted connection. Note the trailing off of the thermal energy. If it were a load imbalance the temperature would be the same throughout the conductor.

Remember, an increase in load will also have a significant effect on increasing the temperature of a high resistance problem (I^2R).

2) Harmonics

Harmonics are currents or voltages that are multiples of the basic incoming 60 HZ frequency serving an electrical distribution system. Possibly the most damaging harmonics are the odd harmonics known as triplens. The triplen harmonics add to the basic frequency and can cause severe overvoltage, overcurrent and overheating. Frequency is not the enemy of the electrical system. The real enemy is increased heat caused by higher frequency harmonics.

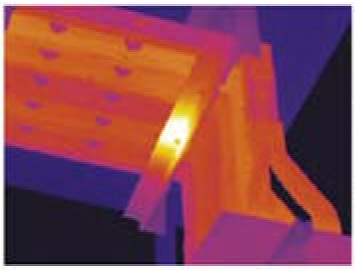
These triplen harmonics can create drastic overheating and even melting of neutral conductors, connections, contact surfaces, and receptacle strips. Other equipment effected by harmonics are transformers, stand-by generators, motors, telecommunication equipment, electrical panels, circuit breakers and busbars.



Harmonicas problems on circuit feeding a data processing room.

3) Induced Heating

Alternating current in electrical systems naturally induce current flow and magnetic flux into surrounding metallic objects such as conduit, metal enclosures and even structural support steel. This phenomenon will occur in areas of high electromagnetic fields such as high voltage equipment, microwave transmitters, and induction heating equipment. This condition can be induced in ferrous material when an electrically induced electro-magnetic field is present. The field induces eddy current which causes subsequent heating and will create true surface temperature changes. An example is ferrous bolts in aluminum electrical bus bar. This is a hard condition to identify and it will appear as something between a faulty component and an emissivity change.

Please Note: We will not go through the apparent thermal pattern variations, but it is just as important for a thermographer to understand the entire ten reasons for real and apparent temperature variations that can be found on an electrical system If the thermographer does not understand these, many false anomalies may be reported. Contact the author for more information on real and apparent thermal variations and how they can be dealt with.

Electrical Applications

This could be an enormous list of equipment and processes since virtually every component from generation to low voltage electronic boards, can and should be inspected. Suffice it to say, the applications fall within four categories:

- **Power generation:** hydro, thermal, and nuclear
- **Power distribution:** transmission, switchyards, substations, and distribution
- **Industrial users:** all process and manufacturing industries
- **Commercial users:** warehouses, office buildings, banks, schools, virtually all buildings

Baltimore Gas & Electric perform infrared electrical inspections on 40,000 miles of distribution lines and 175 substations. The electrical test department is a firm believer in using infrared condition monitoring as a program for increased reliability. In the April 1991 article of Transmission & Distribution, the supervisor says " the infrared equipment allows on-line maintenance with no interruption to service, resulting in continuity of service that avoids about 150,000 customer out-of-service hours a year. The annual inspection tour yields an average of 400 to 450 reports that call for either immediate repair or investigative action, gathered in all types of weather".

Electrical Condition Monitoring

When considering remote diagnostic testing of electrical equipment, infrared thermography is regarded as the most powerful of all diagnostic tools currently available. The list of equipment to inspect is enormous since virtually every component from generation to low voltage electronic boards, can and should be inspected.

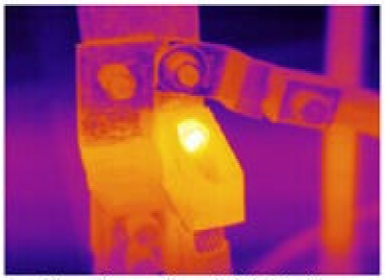
It is very difficult to place a dollar value on the benefits realized from an infrared inspection program because the faults are found and repaired before failure. However, power companies such as Baltimore Electric, Insurance and Risk Management Companies has noted the huge savings received from infrared CM programs.

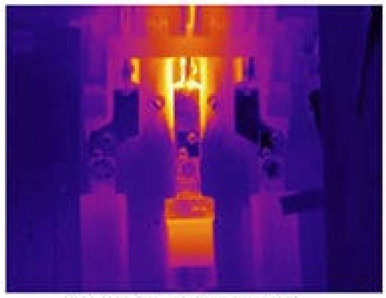
Table 1 itemizes equipment inspected, and in some cases, indicating potential impact and possible savings as reported by various power distribution organizations, industrial plants and insurance companies.

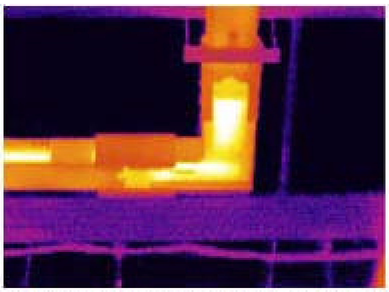
APPLICATION	CONDITIONS DETECTED	POTENTIAL IMPACT
Power Distribution, Capacitors, Lightning Arrestors, Circuit Breakers, Conductors, Splices, Disconnect	Loose/corroded/improper connections and splices, inoperative capacitor, failed lightning arrestors, poor breaker connections, overheating, overloading, conductor strands broken.	Overheating, arcing, burning, fire, conductor strands broken - overhead line could come down. Inoperative capacitor causing lack of protection from power surges and possible early failure of associated electrical equipment, $1,000.00 - $100,000.00. Defective lightning arrestors leaking power to ground. Replacement " $5,000.00. Safety considerations.
Miscellaneous Electrical Apparatus, Switches, Breakers, Load Centers, Motor Control Centers.	Loose or corroded connections, poor contacts, unbalanced loads, overloading, overheating.	Arcing, short-circuiting, burning, fire. 25% of all miscellaneous electrical apparatus failures are caused by loose electrical connections. Average main switchboard or MCC repair, $10,000.00 - $70,000.00; replacement $80,000.00 - $100,000.00. Safety considerations.
Transformers	Loose/deteriorated connections, overheated bushings, poor contacts (tap changer) overloading, unbalanced 3-phase load, blocked/restricted cooling tubes, and fluid level.	Arcing, short circuiting, burning, fires. Rewind (5000 DVA) $40,000.00 - $70,000.00; replacement $80,000.00 - $140,000.00.
Motors/Generators	Overheated bearings, unbalanced load, shorted or open windings, heating of brushes, slip rings and commutators, overload/overheating, blocked cooling passages.	Defective bearings causing damage to iron and/or windings. Defective brushes, causing damage to slip rings or commutators. Resultant damage to windings. Damage to driven object. Motor rewind (5000HP) $50,000.00 - $100,000.00; replacement $1000,000 - $200,000.00. Safety considerations.
Emergency Power - Stand-By Generators, Batteries, Terminal Connections, Contactors, Automatic Stand-By Switches.	Poor battery terminal connections, dead cells in batteries, defective or inoperative contactors or stand-by switches.	Loss of stand-by power for essential services - hospitals, telephone systems, computers, etc.

In an issue of The Locomotive, by risk insurance company, Hartford Steam Boiler, they discuss statistics of Miscellaneous Electrical Apparatus (MEA) failures their clients have experienced over the previous fifteen years. Of the top ten causes of electrical failures, connection problems are number one. The key method chosen to identify these problems is infrared thermography. They say, "An infrared thermographic survey should be performed annually in commercial buildings as well as manufacturing plants. All cable runs, bus ducts, distribution panels, motor control centers, etc. should be checked for hot spots or heat imbalances". "This can identify loose connections, overloads, unbalanced loads, and high neutral currents, that need to be corrected".

Connections- Poor connections are the most frequently found problem on an electrical system. It has been found that routine preventive maintenance on connections does not cure the connection problems, and normally creates additional problems. Routine inspection with a thermal imager lets you know exactly where you problem is, and allows you to schedule maintenance on the real problems.


Thermal anomaly on bolt indicating a bolted connection problem


Poor contact B phase breaker.


Elbow connection on bus bar behind bus enclosure.

Return on Investment

The cost of implementing an infrared condition monitoring program and as the return on investment will vary with the size of facility, complexity of the program, and whether infrared equipment will be purchased, rented or a service hired.

Most utilities and industries recognize that infrared electrical inspections are a key element to providing electrical system reliability. For a large organization purchasing equipment and setting up an in-house infrared condition monitoring program is economically justifiable. Many companies report a complete payback the first time the instrument is used. For example, during the initial inspection at a metal smelter, a hot contactor was found in their main substation which, if not found, would have brought much of the process to a halt costing hundreds of thousands of dollars. On the average, with a trained person, the return on investment is approximately 3 months to one year.

Smaller industrial facilities and commercial building owners can set up an infrared inspection program by using an infrared service company. The return on investment in this situation is also excellent. For example, at one hospital, a one day infrared inspection identified problems that could have cost $12,800.00. Some of the problems were an overheated breaker supplying power to the hospital data processing center; another breaker supplying two elevators; and a badly corroded connection in the breaker of a 50 hp motor.

Another example at a plastics manufacturing plant where an infrared inspection revealed numerous loose, dirty and corroded connections throughout the plants main electrical distribution system. A "worse case" incident in this plant may have resulted in a $12-22,000 direct damage loss, with a 25% production loss for 3 - 4 days, as compared with several hundred dollars for minor repairs, and a few hours downtime for cleaning, replacing and tightening connections. If this is compared with a typical rate for a one day inspection at $850.00, the payback is substantial.

Start the Program off on the Right Foot

It is simple enough to purchase an infrared instrument, all vendors are willing to accommodate you. There is much more to establishing an effective infrared condition monitoring program than just buying a piece of equipment. We have found that most programs fail because the new untrained and inexperienced operator goes into the plant, finds some "hot spots", misinterprets them as problems, repairs are initiated only to find no problem exists. Both the operator and management lose confidence and the equipment is shelved. For example, a newspaper hired an infrared service company to evaluate the bearings on their printing press. A hot bearing was found and the main printing press was shutdown, this severely interrupted production. The bearing was removed and it looked was like new! Unfortunately infrared thermography took the bad rap, not the untrained and unskilled thermographer.

In one of our recent Level I thermography courses, a student was showing some of his reports with "hot spots" on an overhead line. At the end of the course, we asked the student to show his reports again so that the class could evaluate them, he refused. The reason for refusal was he realized most of the "hot spots" were not problems at all but were reflections, solar gain or variations in emittance only. He had been doing infrared inspections for 2 years prior to taking the course!

Training

If maximum benefits are to be achieved from your investment in this powerful, cost reducing technology, a commitment must be made to provide proper training for the operator. If you are going to hire an outside service you must make sure their operators have received and are continuing to receive training and upgrading, just as you would expect from any one coming to your facility to perform other inspection procedures such as x-ray, ultra sound, liquid penetrant etc. Many companies now require thermographers to have a Level II thermographer standing.

Elements of a typical training course include infrared theory and principles, basic heat transfer theory, operation of infrared equipment, how to conduct inspections in facilities and temperature measurement techniques. Training in how to conduct inspections should include what false anomalies to look out for, how to analyze the information and to prepare a report.

With a properly trained individual your infrared condition monitoring program will be off to a great beginning. A trained thermographer will be able to properly diagnose temperature related equipment problems and develop trends to predict equipment failure.

Conclusion

Even though there is effort involved in establishing a program such as this, the benefits are well worth it. Properly implemented and maintained, infrared condition monitoring as a part of a total predictive maintenance program can increase reliability and improve operating profit. Infrared thermography will assist in determining equipment and facility maintenance priorities, enhance operational safety and contribute to a stronger bottom line.