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Classification of Electrical Problems Detected by Infrared Thermography Using a Risk Assessment Process

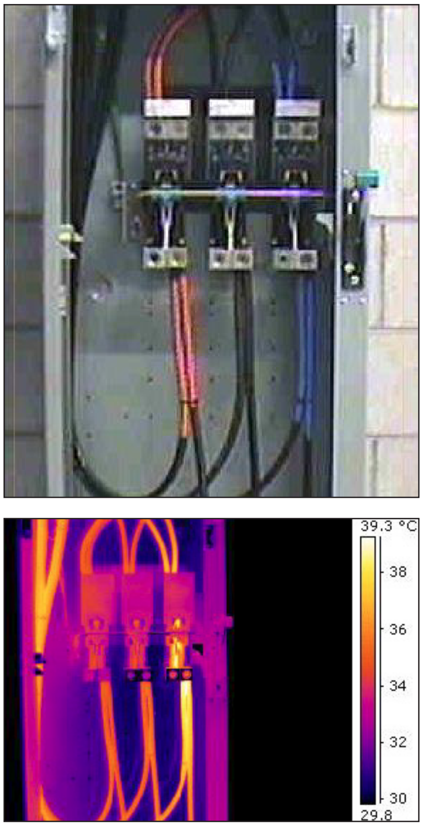


Figure 1. Visual and thermal image of a disconnect switch. The thermal image shows an anomaly in the right phase hinge of the switch.

The traditional method for identifying an electrical connection or component problem is observing it via line of sight with thermal infrared imaging when it is both energized and under load, preferably as high as possible (NFPA 70B).[1] There is, however a great misunderstanding about how to establish the condition of the connection once a thermal anomaly has been found. Historical methods have applied the use of temperature, or temperature rise, established with the infrared camera, as an indicator of the defect severity. Infrared thermography, however, only identifies surface temperature rather than internal interface temperature, and therefore surface temperature taken alone is an unreliable indicator of the fault severity.[2] Some severity assessment methods have combined the use of component specific temperature regimes, while others have used load and environmental correction factors. These also have issues.[3] The closest we have to absolute limits are the maximum temperature ratings of the wire, connector, or device attached to the connector. This limit is typically 60°C, 75°C, or 90°C.[4,5] But often a connection or component below these limits can fail before the next the inspection period. Or, without stressors, may last indefinitely.

An example of an electrical anomaly risk assessment chart is shown in Figure 2. This chart breaks out the two independent concepts of the consequence in the event a failure happens and cross correlates it to the likelihood that the event will actually happen. The Consequence of Failure is shown across the top row with increasing severity from the left to right column. The Likelihood of Failure is shown in the first column proceeding from imminent in the first row to highly unlikely in the last row. We will first discuss some potential suggested criteria for evaluating consequence, and then tackle the second, more difficult topic of evaluating probability of failure.

The core value of thermography is being able to identify that a thermal anomaly exists. While thermography can identify a connection problem through thermal pattern analysis, the connector surface temperature can be very a poor indicator of the nature of the problem or its severity. As illustrated in Figure 1, under a temperature only classification scheme this anomaly, with a very low (a 5°C temperature rise) would be classified by many thermographers as a minor or moderate problem without any consideration for load at the time, downstream component criticality, environmental impact, or life safety. The three phase connections are equally loaded at less than 20% of the rated capacity of the circuit.

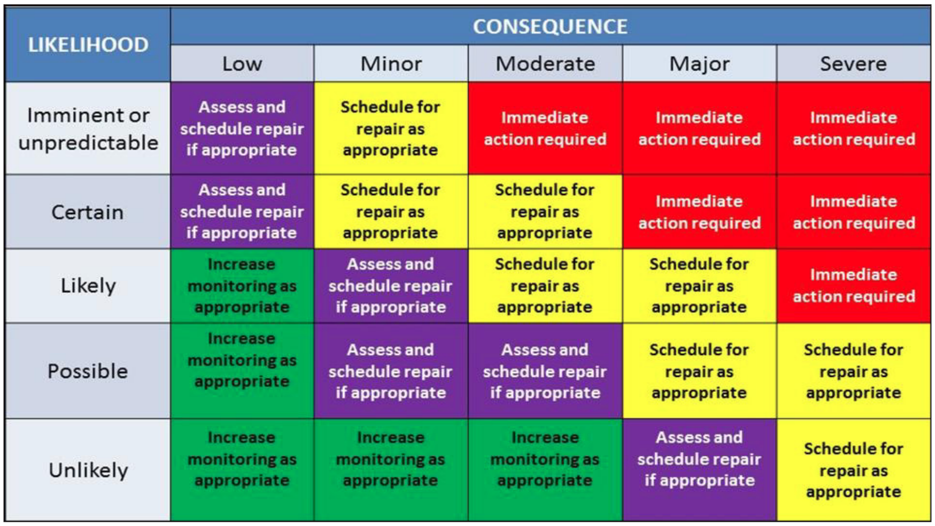
Since fault power increases as the square of the current, the melting voltage could easily be achieved when current is increased to 80% of rated capacity (4x the current = 16x the fault power). This in turn could cause many types of problems including arc flash explosion at the connection, interruption of service, or a more benign failure such as contact welding within the hinge or jaws of the switch. This is particularly critical in a disconnect switch which, if welded closed, could mechanically fail, and cause an arc-blast and severe injury when attempted to be opened.

The reality is that risk assessment is a combination of both probability of occurrence and consequence of event.

In order to prioritize a potential problem we must understand the nature of the problem, the potential failure modes, the stressor(s) involved which will potentially accelerate or cause catastrophic failure, the impact that failure could have on life safety, and the impact failure could have on capital loss or operational interruption. Some attempts have been made to utilize a numerical prioritization scheme[6] and/or matrix system based upon probability of failure and consequence of event.[7] This paper expounds on those principles by formalizing these concepts into a risk assessment chart, much like those used by safety departments and insurance companies.

A Risk Assessment Chart

Many people confuse the concept of risk. Some only think of risk as the consequence. A person that is a parent might consider parachuting too risky because of what could happen if a malfunction occurs. Others only think of risk as the probability of the event happening. A young single person might enjoy parachuting because of the thrill and believing a parachute malfunction will "never" happen. The reality is that risk assessment is a combination of both probability of occurrence and consequence of event. Determining whether the event is "too risky" is based upon the possible range of consequences versus the probability of occurrence. The intersection of the two is then categorized into different categories of risk tolerance.



LIKELIHOOD	CONSEQUENCE				
	Low	Minor	Moderate	Major	Severe
Imminent or unpredictable	Assess and schedule repair if appropriate	Schedule for repair as appropriate	Immediate action required	Immediate action required	Immediate action required
Certain	Assess and schedule repair if appropriate	Schedule for repair as appropriate	Schedule for repair as appropriate	Immediate action required	Immediate action required
Likely	Increase monitoring as appropriate	Assess and schedule repair if appropriate	Schedule for repair as appropriate	Schedule for repair as appropriate	Immediate action required
Possible	Increase monitoring as appropriate	Assess and schedule repair if appropriate	Assess and schedule repair if appropriate	Schedule for repair as appropriate	Schedule for repair as appropriate
Unlikely	Increase monitoring as appropriate	Increase monitoring as appropriate	Increase monitoring as appropriate	Assess and schedule repair if appropriate	Schedule for repair as appropriate

Figure 2. An example of a risk assessment chart.

Evaluating Consequence

Consequence of the failure of an industrial electrical component can often be categorized in order of decreasing importance by: potential for injury; adverse effect on the environment; loss of capital/cost of repair; and the consequence of circuit interruption and/or lost time of electrical service.

Potential for Injury: One means of evaluating potential for injury is to evaluate the consequence of an arc-flash explosion either directly related to the failure of the com-

So long as the appropriate PPE is worn and the inspection distance to the cabinet door is maximized, there is should be a low probability of a lost time injury during this work period.

ponent identified, or the failure of the that component to prevent or mitigate an arc flash explosion elsewhere in the circuit. (Note it is important during this phase that one only think of the consequence of an arc flash explosion and not take the probability of an arc flash occurring – that comes later). The arc flash incident energy level is, in the authors' opinion, an excellent way to evaluate consequence: arc flash incident energy levels of less than 1 cal/cm^2 often have little potential to do harm directly. Incident energy levels of less than 8 to 10 cal/cm^2 typically have little potential to cause collateral damage so long as the door or panel covers are closed. The greatest potential for harm therefore comes during live energized work on that component with the door open (e.g. thermography). So long as the appropriate PPE is worn (by the thermographer) and the inspection distance to the cabinet door is maximized, there is should be a low probability of a lost time injury during this work period. Incident energy levels beyond 10 cal/cm^2 may have arc-blast capability and hence the potential for a lost time injury is higher and the consequences less predictable. This consequence may be best supported as a result of the data provided by a facilities arc flash hazard analysis.

Classification due to consequence of event

Consequence – Low (if ALL the following are satisfied)

- There is no possibility of: injury, production interruption or adverse environmental impact
- The repair cost will be minor and contained within the maintenance budget
- The arc flash level is less than 1cal/cm^2 at the IR inspection distance

Consequence – Minor (if ALL the following are satisfied)

- No lost time injury, unacceptable environmental impact or unacceptable production interruption
- No unpredictable consequential damage
- The cost of repair acceptable but may be outside of budget limits if failure occurs
- The arc flash level is less than 1cal/cm^2 at IR inspection distance

Consequence – Moderate (if the following TWO criteria are satisfied)

- There will be no unacceptable environmental impact
- The arc flash level is less than 8 cal/cm^2 at the IR inspection distance

BUT any ONE of the following criteria exists

- Failure could result in minor injury, but likely not resulting in any lost time injury
- There is a possibility of a production interruption that affects production targets
- There is a possibility of unpredictable consequential damage
- There is a possibility of an unacceptable repair cost

Consequence – Major (if ONE of the following criteria exists)

- There is a possibility of a lost time injury
- There is a possibility of an unacceptable environmental impact
- There could be an unacceptable loss of production
- There could be unpredictable and significant collateral or consequential damage
- There could be an unacceptable repair cost affecting the facility budget
- The arc flash level will be greater than 8 cal/cm^2 at the IR inspection distance

Consequence – Severe (if ONE of the following criteria exists)

- There is a high probability of a lost time injury
- There will be an unacceptable environmental impact

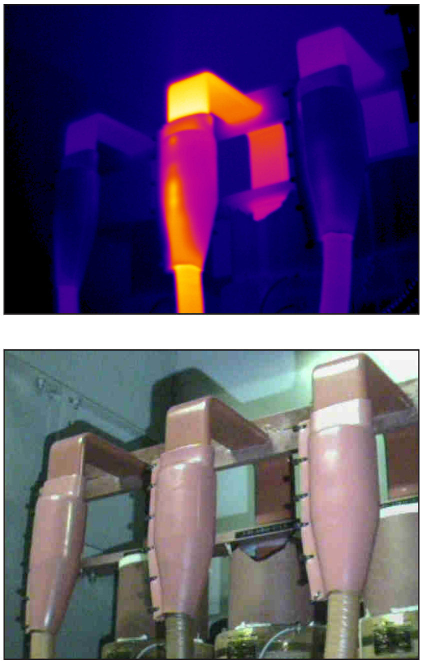


Figure 2. These connections provide power to a 15,000 HP critical motor. Failure of this connection could result in a $1,000,000 per day outage.

- There will be an unacceptable loss of production
- There is unpredictable significant collateral or consequential damage
- There is a possibility of an event affecting the fiscal viability of the facility or company
- There is unpredictable significant collateral or consequential damage due to arc flash or fire

Note: *It is important that the likelihood of occurrence be ignored and only the consequence of failure, if it were to happen, be considered.*

Adverse Effect on the Environment: Circuit failure supplying components for critical environmental control or containment should be assessed for potential of environmental discharge or harm to the environment. Examples may include power for such items as sewage or cooling pumps, circulating fans, pollution abatement equipment, electric incinerating furnaces, and control systems.

Harm to the environment may not only be cause for fines, penalties, or criminal charges, but also may hurt a company's community or global reputation. And in rare circumstances loss of life.

Loss of Capital/ Cost of Repair:
The direct cost of component failure can be categorized into 4 definable limits.

1. The components are relatively low cost, and the repairs can be carried out without excessive labour costs or overtime.
2. The component cost and/or labour cost would exceed budgeted maintenance but can be absorbed by contingency funds or delay in other non-critical repairs.
3. The repair cost could exceed annual budget amounts resulting in impact to the facility bottom line, and or there could be unpredictable collateral damage. Unpredictability usually comes when the energy levels have reached arc-blast capacity and collateral damage to adjacent equipment and/or fire is possible. Again it is extremely important in this process not to consider whether an arc blast will happen, but what are the possible consequences if it does happen).
4. The failure of the component itself could result in a fire or explosion which destroys all or part of a facility (e.g. an electrical fire in a lumber mill or petro-chemical plant).

Component Failure/Loss of Electrical Service: This is a broad category and often thought of as simply the time that the process is interrupted until the electrical repairs are made. Particular attention, however, should be paid to evaluating the consequence of circuit interruption where the component failure is not catastrophic, but perhaps has failed closed, or will not operate properly when called upon. Examples of this would be a transfer switch which fails to operate, an isolating switch which has welded itself closed and then cannot isolate the circuit for maintenance; or a load-tap changer that will not switch properly. Also such things as a component failure downstream of a generator (e.g. a main output transformer bushing) that when open circuit happens, and emergency shutdown is initiated, a generator bearing fails, or a high pressure steam relief valve opens. Collateral damage, particularly from an arc-blast explosion, can often result in lengthy repair and replacement time and necessitate additional cost for expensive temporary measures such as generator, transformer or distribution equipment rental and temporary wiring.

There are many possible reasons for a warmer than normal electrical connector, the most obvious and misdiagnosed of which is a "loose" connection.

Evaluating the Likelihood of Failure

Understanding the root cause of an electrical connection "functional failure" is essential to assessing the likelihood of catastrophic failure.[8] Unfortunately an infrared camera is not a thermal x-ray – it only observes infrared emitted energy levels from a surface (which may or may not accurately calculate into of actual surface temperature) and not the actual interface temperature at the connection. According to the second law of thermodynamics, in steady state heat transfer, there will always be a conductive thermal gradient between the actual surface temperature and internal contact temperature. Both forensic analysis, and thermal modelling have demonstrated that the temperature at the internal contact points (in a faulty connection under load) can be much higher than the external temperature of the surface.[9]

Reasons for a connector to display a thermal anomaly: There are many possible reasons for a warmer than normal electrical connector, the most obvious and misdiagnosed of which is a "loose" connection. This term alone is a misnomer and should properly be termed "under-torque". Even if a connector has the proper torque initially, the contact force in the electrical interfaces may decay due to poor connector design leading to overheating, ensuing metal creep/flow and the consequential further decrease in contact force. In addition to issues related to under-torque, a connection could be warped, dirty, corroded, or even over-torque to the point where it has been cold-worked with resultant stress cracking.

The reasons for a connector thermal anomaly may include:

- Improper design
- Material compatibility
- Improper preparation and assembly
- Under-torque
- Over-torque
- End of Life

Why would a thermal anomaly get worse on its own? The easy answer to this is that something is occurring to continually reduce the contact surface area of the connection. The common reason for this is thought to be fretting corrosion which is the micro-movement of one surface against the other. Three potential sources for this movement are external vibration, harmonic vibration, and thermal cycling. A second cause for surface area reduction could be the presence of micro-arcing in the air gap between a warped or mal-fit connection where a slight air gap exists. A third cause for this surface area reduction is the presence of an external corrosive agent.

The most troubling aspect of all the above factors is it is unlikely that without further testing, or perhaps even without disassembly, we may never be able to ascertain what is causing the lack of contact. It may be possible, in some instances to use an airborne ultrasonic device, to detect if there is internal arcing within the connection but this is just one possible internal phenomenon. In some instances it may be possible to measure a voltage drop across the connection in which case the impedance and proximity to melting voltage can be established. But in most cases this is not possible, safe, and/or practical.

Stressors which may accelerate time to failure can include:

- Excessive vibration
- Corrosive environment
- Fatigue and/or start/stop cycling
- Excessive/thermal environment
- Internal micro-arcing
- Improper operation
- Single event over-stress

An electrical connection and many components, typically may have two failure modes: progressive and instantaneous. Progressive failures can take from months to years depending on the type and frequency of stressor(s) present, until finally melting voltage within the connection occurs (note: a discussion of connection and contact melting voltage can be found in reference 10). A single event over-stress typically is the cause for an instantaneous failure. The most common single event over-stressor is the in-rush current experienced during start-up of a motor. A less frequent (and less predictable) but usually much more severe stressor, is the occurrence of a fault current. Other single event stressors could be: circuit breaker operation and consequent circuit switching and/or re-closure loads; lightning strikes; or even such things as pile driving next to building basement load-center, or blasting next to a substation.

Reliability of radiometric measurement: One other consideration that needs to be taken into account is the reliability and accuracy of any radiometric temperature measurements. Any temperature or differential measurements made on surfaces with low and/or varying emissivity, or with varying thermal background should be considered to be unreliable. Any failure analysis which includes this measurement should be also considered to be unreliable and therefore failure time unpredictable. Contrary to popular opinion low and varying emissivity affects differential measurement accuracy as well as actual temperature accuracy.

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Evaluating and classifying the Likelihood of Occurrence.

Failure – Imminent or Unpredictable (if ONE of the following conditions exists)

- A material temperature or manufacturer's limit has been exceeded
- A high delta T (above normal operating temperature or ambient) and stressors* are present
- Temperatures or Delta T is unreliable or inaccurate because of emissivity, background etc.
- The load is low at time of inspection and can increase 50% or more at any time
- Physical damage is observed
- There is a high thermal gradient
- There is an alternative parallel path of conductive heat flow
- There is significant convection present
- Voltage drop is likely at or above the melting voltage at full load

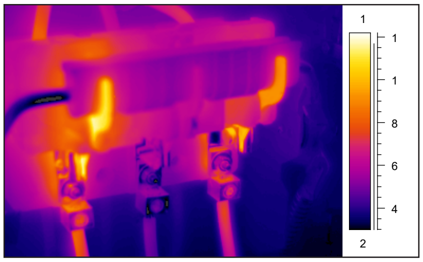

Figure 3. A “large” 90°C temperature difference which after 3 years still had not failed (high constant load, no stressors)

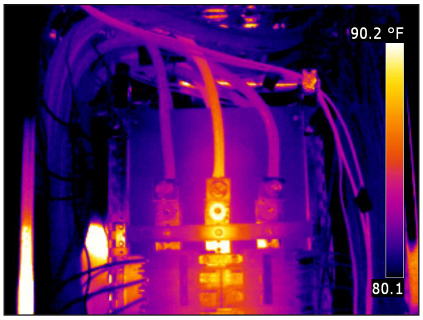

Figure 3. A “small” 5°C temperature difference which, due to load, needed to be shut down immediately

Failure – Highly Probable (before next scheduled inspection if a low delta T above normal is present and any ONE of the following condition exists)

- A material or manufacturers limit will likely be exceeded and/or stressors are present
- The load can increase up to 50% above the inspection level during the inspection period
- The voltage drop exceeds 10% of material melting voltage

Failure – Likely (may occur within the inspection period if a low delta T is present but ONE of the following conditions exist)

- Multiple stressors are present
- Loads may increase up to 25% above inspection levels
- The Voltage drop exceeds 1% of the melting voltage

Failure – Possible (unlikely within the inspection period if the ALL of the following conditions exist)

- Radiometric temperatures are reliable (high emissivity, controlled and background etc.)
- Low delta T above normal operating temperature
- No convection was present during the inspection
- There is a low thermal gradient
- There is no alternative parallel path of conductive heat flow
- The loads are not likely to increase and stressors are not present
- The voltage drop <1% of melting voltage

Failure – Unlikely (within inspection period if ALL of the following conditions exist)

- Radiometric temperatures are reliable (high emissivity, controlled background etc.)
- A low delta T above normal operating temperature;
- No convection was present during the inspection;
- There is a very low thermal gradient;
- No arcing is detected;
- There is no alternative parallel path of conductive heat flow;
- The loads will not increase and stressors are not present;
- The voltage drop <0.1% of melting voltage.

However, failure could occur if there is single event stressor happens (e.g.: fault current,overload, loss of cooling, major line surge, etc.).

Examples of how situation can affect failure time: The following are some examples to illustrate why progressive failure times will be different given different situations.

Situation 1. A normal maximum current is flowing in the circuit every day for 24/7. The room air temperature is controlled and contains no adverse corrosive agents nor external vibration. Failure mechanisms or stressors in a faulty connector are minimized.

Situation 2. Exactly the same as Situation 1 but the circuit is turned off and on frequently every day. A failure mechanism exists due to internal arcing, and/or fretting corrosion created by thermal expansion and contraction as the thermal anomaly in the connector heats up and cools down each time the circuit is turned on and off respectively.

Situation 3. The same as situation 1 but the connector thermal anomaly is located in a water treatment facility, public swimming pool, food processing plant, barn, pulp and paper mill, or chemical plant where corrosive environments such as chlorine, ammonia or sulphates are present. A failure mechanism exists due to the presence of a corrosive element.

Situation 4. The same as situation 1 but the thermal anomaly is located in an environment with externally induced vibration. While some connector designs expect this (e.g.: a motor junction box connector) other sources of vibration are not always anticipated by the electrical design engineer (the proximity of a reciprocating compressor, construction, truck traffic, etc.).

When multiple stressors exist simultaneously the time to failure can be quite rapid. A thermal anomaly in a connection in a 50 HP motor control unit in a nuclear power plant may have a time to failure of 3 to 4 years resulting in a time to inspection of 2 years (which is the EPRI recommended maximum inspection time interval) while in a meat packing operation or water treatment plant with all 4 stressors working in combination failure time can be as low as 6 months requiring a consequent inspection interval of every 3 months.[8]

Failure prediction of an electrical connection based upon temperature alone is not accurate, and at times can be very misleading.

Summary

Failure prediction of an electrical connection based upon temperature alone is not accurate, and at times can be very misleading. Determining whether a thermal anomaly is a potential or functional failure will be extremely difficult unless we know about: the problem root cause; all the materials involved along with their thermal and other material limits; the extremes of load variance; and the unusual environmental and operational stressors that will be placed on the component. Therefore, the easiest and least risky way of dealing with an electrical thermal anomaly is to immediately de-energize, disassemble, investigate and repair or replace as appropriate. Maintenance resources, or operational circumstances, however, do not always afford the luxury of this approach. In this event a risk management approach to repair prioritization, such as presented in this paper, should be undertaken.

A risk management approach for the necessary actions required for a thermal anomaly identified with infrared thermography can extend beyond electrical applications. It can be utilized anytime there needs to be need a justification for resources to investigate and/or repair the cause for the anomaly. It is particularly appropriate for decision making anytime technical or maintenance resources must be contracted. A risk management approach, however, typically implies that more information is available than just a thermal image. This includes such things as design and construction information; material limits; documenting operational conditions and then knowing the variances from conditions that will occur; understanding all potential failure modes; and finally brainstorming all potential consequences from the various failure modes. Applications where this could be useful could include building investigations for heat, air and moisture deficiencies; machinery diagnostics; and applications involving furnaces, heaters and process vessels.

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References

[1] NFPA 70B, [Recommended Practice for Electrical Equipment Maintenance], National Fire Protection Association, (2006).

[2] McIntosh, G.B., "NFPA 70B Fault Severity Guidelines for Electrical Thermography", Ontario Electrical Contractors Magazine, (2010).

[3] McIntosh, G.B., "Myths and truths about wind and load correction factors", white paper, The Snell Group, http://www.thesnellgroup.com/contact-us/receive-white-papers (2008).

[4] UL standard 489, [Molded-Case Switches and Circuit-Breaker Enclosures], Underwriters Laboratories, (2013).

[5] Pauley, J., "Wire Temperature Ratings and Terminations", Bulletin No. 0110DB9901R2/02, Square D Company, (2002).

[6] Huff, R. Snell, J., [Electrical Inspections Utilizing Infrared Thermography], Short Course Manual, Thermal Solutions Conference, The Snell Group, (2001).

[7] The Snell Group, [Level I Thermographic Applications Manual], The Snell Group, Barre, VT (2008)

[8] McIntosh, G.B. "Condition Assessment of Electrical Connections Utilizing Infrared Thermography", Quantitative Infrared Thermography (QIRT) Conference Proceedings, (July 2014).

[9] Timsit, R.S., Wilson, C., McIntosh G., "Contact Spot Temperature and the Temperature of External Surfaces in an Electrical Connection", Proceedings of ICEC&ICREPEC, (May 2012).

[10] Timsit, Roland, S., "The Temperature of an Electrically Heated Contact Spot", The Connector TekNote, Timron Scientific Consulting Inc., http://www.timron-inc.com/teknoteMay2001.html (May 2001).