Priority Table Rationale for Electrical Substations

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ABSTRACT
It would seem that every thermographer has their tried and true approach to determining the severity of a heating component. In the electrical utility industry, the decision to remove a heating component for repair is not a trivial one. Generation may be bottlenecked, customer's supply put at risk or revenue streams may be lost as a result of the decision to repair a component before its next scheduled maintenance interval. At a minimum, valuable resources must be re-allocated from other maintenance activities to repair the defect. These possible impacts must then be weighed against the probability of failure and the impacts of failure to the customer. This paper explores the “Priority Table Rationale” with concrete examples from Hydro One’s power system.

INTRODUCTION
Hydro One (formerly Ontario Hydro) has used IR Preventive Maintenance since the late 1970’s, long before Preventive Maintenance or Condition Based Maintenance became the industry norm. In the early years of IR, as with most emerging technologies, the data from heating equipment was easily obtained. The dilemma was how to act on the information gathered and how to integrate this information into a cohesive maintenance strategy. Thermography, while based on exact science, is anything but exact when practiced in the field due to the high number of uncontrollable variables. The challenge then for the thermographer and the maintenance team is to make an informed decision taking into account the amount of risk the company is willing to assume for a given asset.

PRIORITY TABLES – WHAT ARE THEY AND WHERE ARE THEY USED
- Based on Temperature Rise
- Used to simplify prioritization for repair/action
- No single industry standard
- Some utilities use the same temperature rise criteria for all components
- Hydro One uses a component based approach with Delta T readings
- Tables are guidelines only. The informed thermographer alters the table recommendation often due to field conditions such as wind, ambient temperature, load, and system component criticality.

PRIORITY EXAMPLES FROM OTHER ORGANIZATIONS
Let’s briefly examine some examples of priority guidelines from other organizations.

NETA Guidelines
- 1ºC - 10ºC O/A  POSSIBLE DEFICIENCY
  1 ºC - 3ºC O/S
- 11ºC - 20ºC O/A  PROBABLE DEFICIENCY
  4 ºC - 15 ºC O/S
- 21 ºC - 40 ºC O/A  DEFICIENCY
  >15 ºC O/S
- >40 ºC O/A  MAJOR DEFICIENCY
  >15 ºC O/S
Electrical Severity Classification - Direct Readings
(Rise - Degrees C)

<table>
<thead>
<tr>
<th>Source</th>
<th>Most Critical</th>
<th>Intermediate</th>
<th>Normal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Com-Ed</td>
<td>&gt; 75 C</td>
<td>35 to 75</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>ConditionAnalysing.com</td>
<td>&gt; 30</td>
<td>10 to 30</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>Mil Spec</td>
<td>&gt; 40</td>
<td>10 to 40</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>US Nuclear</td>
<td>&gt; 35</td>
<td>5 to 35</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>CES - Overhead</td>
<td>&gt; 21</td>
<td>6 to 21</td>
<td>&lt; 6</td>
</tr>
<tr>
<td>CES - Underground</td>
<td>&gt; 10</td>
<td>5 to 10</td>
<td>&lt; 5</td>
</tr>
</tbody>
</table>

It is very clear from this sampling that the priority for repair for a given defect can vary greatly from one organization to another. All these industry examples were obtained from the Infrared Training Center Level I course manual.

**HYDRO ONE PHILOSOPHY**

- Based on field results over 30 year period.
- Based on temperature difference between component under evaluation and other components with similar load.
- Comparative in nature.
- Uses a class of defect to prioritize repair.
Severity rating (most severe to least severe) | Severity Description
--- | ---
Technical judgment. Outside rating system - Extreme severity | Immediate intervention based on personnel safety, circuit criticality, risk to adjacent circuits etc.
CR4 | Most severe rating. Failure could be imminent – repair in three days.
CR3 | Very severe rating. Requires repair in 30 days or less.
CR2 | Minor severity. Rescan next scheduled IR or one year.
CR1 | Not critical, defect in initial stage. Note deterioration over time.

These classes of defects are a good start toward a complete and functional priority table. They are a means by which your organization can respond in a consistent manner to the defects that threaten the integrity of supply to the customer.

Next you need to consider the type of component under evaluation. A disconnect switch for example, which by its nature is a current carrying device, can rise in temperature 20° C at the jaw/blade connection and still function perfectly. A surge arrester is a good example of a device not designed to carry current under normal system conditions. Therefore the surge arrester temperature should not rise more than a few degrees over ambient temperature. The same 20° C rise given for the disconnect switch would end in certain catastrophic failure.

The last bit of information required to complete our table is the temperature rise for the failing component type and the reference used to give that temperature more relevance under operating conditions.

Let's look at examples of defect heating by component type to try and complete our emerging priority table.

**BOLTED CONNECTORS**

Bolted connectors comprise a very large percentage of the defects found in a typical HV transmission utility. It is important to get a priority for repair that does not waste company resources repairing connectors that are not in immediate threat of failure. Many contractors sent me IR images of our facilities, pointing out connectors a few degrees above ambient and state that repairs must be made or we risk imminent failure. Nothing could be farther from the truth. Of course connector failure can and does happen: witness the following example as shown in Figures 1a and 1b.

![Figure 1a. Thermogram of NEMA bolted connector.](image1)

![Figure 1b. Failure to act resulted in unfortunate component failure.](image2)
Connector is rated at 3100 Amps and carrying 1800 Amps at the time the image in Figure 1a was captured.

- Delta T is 41°C.

**WE FAILED TO ACT IN TIME!**
- Reality check! Scheduling, resources, outage window difficult to coordinate!
- 30 days elapsed from IR scan to failure.
- Note: copper melts at 660°C and aluminum at 1083°C.
- Remember we are recording BULK temperature. Micro spots inside the connector can reach 4 to 10 times our bulk temperature.
- Current readings at time of failure are unavailable, but it is a fair assumption that current through the connector exceeded the previous value of 1800 amps and was a factor in escalation of the problem.

![Figure 2. Thermogram of bolted connection on wave trap](image)

Note in Figure 2, there appears to be but one bolt carrying all the current. That’s why it is so hot. Watch for this! Connectors in last stages of failure often have a single bolt carrying current.

**LESSONS LEARNED IN THESE EXAMPLES:**
1. Our table must be conservative to account for changing conditions, i.e. loading, ambient temperature, and wind conditions encountered in field evaluation. Also the realization that we can only record bulk temperature, not temperatures inside the connection, is a problem that cannot be overcome to arrive at precise evaluation.
2. It is the basic metallurgic properties of copper and aluminum melting temperatures noted above, which leads us to the next realization. That realization is that connectors made solely of copper are more robust than those connectors with some aluminum composition. Had the connector above been made solely of copper, the outcome would have been better; or at the very least, the failure may have been delayed for some period of time (months likely). Our emerging table must reflect these realities.
3. Since repair of failing components cannot always be repaired in a timely manner due to non-technical constraints (e.g. scheduling challenges), a conservative approach is further reinforced.
4. Other visual indicators (e.g. single bolt above) may justify raising priority to next highest level: i.e. CR2 to CR3.

**DISCONNECT SWITCHES**
Disconnected switches can often be problematic due to their very nature. Sometimes the connection doesn’t align properly. Sometimes there is poor connection due to corrosion and so on. Figure 3 shows a thermogram of a disconnect switch problem.
Figure 3. 230 kV Disconnect switch thermogram

- 315° C delta T. Hinge of switch deteriorated.
- Major internal part replacement was necessary.
- Switches will often survive high delta T without experiencing failures. They are typically of a very robust design.

RECLOSERS, SURGE ARRESTERS, AND CABLE TERMINATORS

Figure 4a. Recloser thermogram Figure 4b. Catastrophic failure of recloser

Though the recloser surface temperature read only 17 C above ambient, this is an indirect reading. Internal temperatures were much higher. Result was catastrophic failure of the recloser.
Figure 5. Surge Arrester Thermogram

- Center Section is faulted.
- Point of conduction 33% reduced.
- Not designed to carry continuous current. Risk for explosive failure.
- Exclusion zone indicated until repairs are made. Note porcelain composition.

LESSONS LEARNED IN THESE EXAMPLES:
Personnel SAFETY must be taken into account when developing priority tables.
Safety of Infrared surveyors, utility staff, and the public at large must all be considered in the table matrix.

Components that can affect staff safety due to possibility of explosive catastrophic failure:
- Porcelain cable terminators (potheads).
- Porcelain surge arresters.
- Capacitive voltage transformers (CVTs).
- Station battery banks (lead-acid).

TRANSFORMERS
Transformers are often one of the more expensive assets on a transmission system. This means that transformer issues must be vigorously pursued and the priority for repair is conservatively rated. Though few defects of this type are encountered, the system impacts are often serious.

Therefore, unlike our rationale for bolted connectors, we can and will tolerate false positive reports. It is better to open a transformer tap changer for example, and occasionally find no significant fault than is to suffer even one costly failure that could have been prevented.

Figure 6 shows a thermogram of a transformer bushing that shows internal heating. This is an indirect measurement, so the internal temperatures will be considerably higher than on the surface. In this case the draw lead internal connection was high resistance. This could lead to catastrophic transformer failure. Oil on the ground, often a good clue, could be misleading and result in incorrect diagnosis.
Figure 7 shows another indirect measurement, a load tap changer. In normal operation, the tap changer tank will run cooler than the main tank. Here, there is almost a 7°C temperature increase of the tap changer tank over the main tank. Often, a thermal anomaly such as this will be followed up with another diagnostic. In the case of load tap changers, an oil sample can prove informative. In this case, the collector ring on the tap changer selector switch was heavily carbonized as shown in Figures 8a and 8b.

Transformer Lessons Learned

- Tank readings are significant indicators of internal problems – see also case study below.
- Many defects such as bushing draw leads can compromise the health of transformer and reduce their lifespan.

**EXTENUATING CIRCUMSTANCES – TABLES ARE SOMETIMES INADEQUATE**

Many times, no matter how critical the infrared evaluation is, there may be system events that prevent you from forcing critical elements from service until the very last moment before they fail. In this case, it is prudent to run a study of the component heating behavior. At times, factoring in the criticality of the component, around-the-clock assessment could be deemed necessary. An example of such a critical component may be a unit circuit breaker controlling the output of a 4000 MW nuclear reactor. The range of options in such a case might be:

1. Force the unit circuit breaker from service immediately and suffer the consequences! Usually there is a better time than NOW to exercise this career-limiting action!
2. Monitor the degradation and force from service when deterioration is escalating toward immediate failure.
3. Limit the load on a component. Many defects are stable in the short-term if the loading is kept stable.
4. Plan to off-load the component by re-routing the load to other subsystems. This option is not always possible.
5. Contingency study.

CASE STUDY USING OIL-FILLED 750 MVA TRANSFORMER DEFECT

Let's explore which option or priority for repair best fits the following example. It is clear a simple table based determination is not the best option. More information is needed to decide the best course of action.

PROBLEM:
Figure 9a is a thermogram of the side of a transformer tank wall. Heating was due to loose ground shield attachments on tank wall. Here are the details:

- 230/500 kV 750 MVA auto transformer
- Transformer replacement: $3M - $4M
- Repair: $3M, de-tank necessary making scheduling with turnaround problematic
- Positively Identified Using IR and DGA results. Temp delta 40 C to 140 C

Figure 9a. Thermogram showing heating caused by stray current at ground shield.

Figure 9b. Standoff Insulator for Ground Shield. Heating location confirmed by blue discoloration of copper button.

Note: oil is a great coolant and works against successful identification using IR methods alone. Your priority for repair in this example must be on a case-by-case basis due to the high cost of replacement or repair.

ADDITIONAL FACTS:
- DGA indicates CO₂: no methane, hydrogen, acetylene – these gases are common to most failure modes
- This is because defect temperature is sub 150 C
- Suspended carbon produced at heating location can lead to core failure
- Total five units affected.
  Internal inspection indicated that there was a good cross-correlation between 120 degree Celsius delta T Thermogram (or greater) PLUS CO₂ indicating advanced shield deterioration with suspended carbon in oil.

ACTIONS
- 1 unit has been replaced
- 1 unit scheduled for replacement
- 1 unit starting to deteriorate
- 2 units stable – no problem yet
- Infrared scans every 6 months, further analysis and actions as temperature deteriorates.
RESULTS
The lifespan of a $3M asset is greatly increased without undo risk for our customers.

A WORD OF CAUTION ABOUT COMMISSIONING
Commissioning defects: meaning defects discovered immediately following new construction of substations has special considerations. The normal assumptions and historical evidence that support our priority table for component degradation really don’t fit well for this case. These defects are typically the result of improper assembly, loose connector bolt etc., and often fail very quickly once placed on load. The thermographer therefore must be very conservative in the recommendation for repair to avoid catastrophic failure.

A WORKING PRIORITY TABLE
Here is an example of a working priority table similar to the table used by Hydro One Transmission Stations.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Reference</th>
<th>°C rise</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CR1</td>
<td>CR2</td>
</tr>
<tr>
<td>Transformer under-load Tap changer</td>
<td>Transformer tank</td>
<td>---</td>
</tr>
<tr>
<td>Transformer and breaker bushing (not the bushing connector)</td>
<td>Bus</td>
<td>2</td>
</tr>
<tr>
<td>Clamps, Connectors and Bus supports (with any aluminium)</td>
<td>Bus</td>
<td>2</td>
</tr>
<tr>
<td>Clamps, Connectors and Bus supports (all copper with steel/bronze bolts)</td>
<td>Bus</td>
<td>2</td>
</tr>
<tr>
<td>Disconnect Switches</td>
<td>Bus</td>
<td>20</td>
</tr>
<tr>
<td>Surge Arresters</td>
<td>Ambient</td>
<td>2</td>
</tr>
<tr>
<td>Capacitors-Power Internally Fused</td>
<td>Bus</td>
<td>0-18</td>
</tr>
<tr>
<td>Capacitors-Power</td>
<td>Bus</td>
<td>2</td>
</tr>
<tr>
<td>Capacitors-CVT</td>
<td>Bus</td>
<td>-</td>
</tr>
<tr>
<td>RG (resistive gradient) Insulators</td>
<td>Bus</td>
<td>5</td>
</tr>
<tr>
<td>Potheads</td>
<td>Ambient</td>
<td>-</td>
</tr>
<tr>
<td>Bus or Conductor (not connector)</td>
<td>Ambient</td>
<td>-</td>
</tr>
</tbody>
</table>

** Possible safety issue: Refer to Technical Services.
REFERENCES

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ABOUT THE AUTHOR
Dale Avery is a Level II thermographer and has been part of the Hydro One (formerly Ontario Hydro) Infrared program for most of his 29 years with the company. He currently manages the IR program at Hydro One for Stations (not lines) from a Technical Perspective. Additionally Dale has technical responsibility for all Metalclad and GIS (gas insulated substation) equipment.