New Dielectric Inhibits Virtual Junction Errors In Type K Thermocouples

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ABSTRACT
A new dielectric mineral insulation material that reduces or eliminates virtual junction errors has been introduced in the manufacture of thermocouples. It replaces the Magnesium Oxide (MgO) dielectric mineral insulation used by all current manufacturers. Virtual Junction Errors most commonly appear when the temperature along the shaft of the thermocouple is higher than the measuring tip and the thermocouple starts measuring the intermediate temperature, not the temperature at the tip. Some fascinating experiments show this material eliminates or greatly reduces Virtual Junction errors resulting in improved measurement accuracy and temperature control of furnaces. The experimental setup and results are presented. Thermocouples made with this new material, called MI-Dry™, will have a great impact in improving instrumentation of furnaces, pyrolysis units, and turbine engines. They are already being used with excellent results in furnaces and reactors in Steel and Chemicals plants.

INTRODUCTION
Metal sheathed mineral insulated Type K thermocouples are used in the fireboxes of many boilers, pyrolysis reactors, turbine engines and the like where the conditions are very severe. It is not unusual to see thermocouple installations attempting to measure temperatures of 1500 to 2200 F even though this approaches the limits of use of even the most rugged thermocouples. A thermocouple is supposed to measure the temperature at the tip where the dissimilar metal wire legs are joined. Un-impaired thermocouples do a very good job of doing just that. However, several physical and chemical
mechanisms can cause impairment of a thermocouple resulting in erroneous readings that are often hard to detect. If a thermocouple fails catastrophically it is easy to detect. However, more often a thermocouple fails gradually through decalibration of the thermoelement wires or degradation of the insulation separating them. Advances in materials of construction have primarily focused on the metal alloys for the wires and the protective sheath. Significant improvements in alloys have been made such that thermocouples are being pushed to new limits. Little has been done to improve the properties of the dielectric mineral insulation that electrically isolates the metals from one another. Magnesium Oxide (MgO) is the dielectric of choice being used in over 95% of the thermocouples manufactured today. As we have been able to push the metals to higher and higher temperatures, the MgO has become the weakest link. Recently a new mineral insulation material has been developed and is being used in manufacturing Type K, N and J thermocouples. It provides superior performance at the higher temperatures demanded of these thermocouples today. It is called MI-Dry™.

VIRTUAL JUNCTION ERRORS

The ASTM Manual on The Use of Thermocouples in Temperature Measurement (4) provides the following definition of Virtual Junction: **Virtual Junction, n – in thermoelectric thermometry; a location along a homogeneous thermoelement that marks a segment endpoint that (for purposes of analysis) functions as if it were a real thermocouple junction.** Interestingly nothing else is said in the manual about virtual junctions.

Because of their ruggedness and wide temperature range, Type K thermocouples are by far the most common thermocouples used for high temperature measurement in industry. The thermocouple elements have a measuring range from –400°F to as high as 2500°F (5). For severe service these thermocouples are constructed with high temperature protective sheath materials, such as Stainless Steel and Inconel 600, best suited for the process environment in which they will be used. Magnesium Oxide (MgO) is used as an electrical and chemical insulant, or dielectric, to separate the thermoelements from one another and from the sheath. As a thermocouple is brought up to high temperature, the electrical resistance (commonly called IR) of the dielectric, as with most materials, diminishes.

If the electrical resistance of the dielectric gets low enough, a conductive path can form causing electrons to flow across the insulation. If the point at which the electrical path is formed is not at the measuring tip a “Virtual Junction” is formed. Virtual Junction Error most commonly occurs in a thermocouple when, at some point along the thermocouple’s length (between the hot tip and the measuring end) the temperature exceeds the temperature at the thermocouple’s hot tip and breakdown of the dielectric occurs. This can happen in furnace and engine applications from flame impingement, concentrated radiation, etc. somewhere along the thermocouple’s length. The increased temperature at the midsection of the thermocouple can accelerate the breakdown of the dielectric mineral insulation and allow electrical shunting between the thermal elements. This shunting causes incorrect temperature readings because the thermocouple is effectively shortened and begins measuring the temperature gradients from a point different than the tip.

An inverse relationship of IR to temperature is a common electrical property of most materials. Loss of insulation resistance can also be enhanced by chemical changes in the dielectric. Since MgO is...
hygroscopic, it absorbs water during the manufacturing process when exposed to air. This is a problem for thermocouple manufacturers. Care is taken in thermocouple manufacture to dry or “bake out” the sensor before it is sealed to eliminate as much moisture as possible from the inside of the sensor. It is believed that moisture trapped inside the sensor may react with the MgO causing it to lose its insulating properties. This can also cause a virtual junction.

THERMOCOUPLE DECALIBRATION

The temperature measurement in a thermocouple is derived from the now famous observation by Tom Seebeck in 1821 that when two dissimilar electrically conductive materials are joined at one end and that end is maintained at a different temperature than the open end, a voltage or emf (electromotive force) is generated across the open end. Further Seebeck observed that that voltage correlated with the magnitude of the difference in temperatures of the two ends. We now know that the emf is not generated at the junction of the two materials, but rather along the length of the two materials as the temperature changes from one end to the other (2). In other words, the emf is generated in the temperature gradient. This makes it very important to have materials with uniform composition from one end to the other so that the same signal generates regardless of the positioning of the temperature gradient along the length of the wires. It is also important that the insulating material surrounding the wires in a thermocouple be stable to protect them from contamination and also to avoid shunting or short-circuiting the wires.

A primary mechanism for thermocouple decalibration and impairment is inhomogeneity in the wires caused by a change in composition of the wires (1). This is frequently due to migration of impurities within the sensor from wire to wire or sheath to wire. Small changes in composition cause changes in the emf signal generated by the wire pair and cause errors in the temperature estimate. In addition to electrical insulation, another function of a good insulant is to block the migration of impurities. Some impurities may actually come from the mineral insulation itself. Pure magnesium oxide (MgO) is actually quite a good insulator. However, its penchant to take up and retain water can ultimately affect its performance. Moisture trapped by the MgO decreases its insulation resistance, causes chemical changes in the material and aids in the transport of ions within the sensor. Moisture also contributes to corrosion of some of the alloy materials used in thermocouples. Moisture can enter during the manufacturing process when the cable is open to form the thermocouple junction and to expose the lead wires. Moisture can also be absorbed if there is a breach in the sheath or thermocouple sealant. This problem is often encountered if the thermocouple is stored for some time before use. Without great care in manufacturing techniques the insulating properties of MgO can easily diminish.

Virtual junction error is sometimes mistaken for decalibration due to inhomogeneity. It is a different process, but is also a result of insulation breakdown at the conditions the sensor is subjected to in the process application.

THE NEW DIELECTRIC

The new dielectric mineral insulation material is an extremely stable high performance ceramic made specifically for use in mineral insulated metal-sheathed cables used to make thermocouples and RTDs.
This material is much less hygroscopic than MgO and has better electrical resistance properties in thermocouple service than MgO. It can be fabricated into thermocouple cable in the same manner as MgO. This new material not only has superior electrical resistance, but it blocks the diffusion of trace elements into thermoelement wires. Because it is virtually non-hygrosopic, the new material reduces the ingress of moisture into the cable interior. This significantly increases resistance to corrosion and other processes that promote thermocouple decalibration. The new ceramic itself is non-corrosive to metals up to 2000°C, whereas MgO will react with most metals above 480°C. It exhibits negligible reaction with conducting wires or other materials up to 1300°C. While insulation resistance of thermocouples is a function of geometry as well as the insulant, similar thermocouples fabricated with MI-Dry™ consistently exhibit 50-100 times higher insulation resistance than MgO insulated thermocouples (See TABLE 1 and FIG. 1). This reduces or prevents virtual junction and shunting errors. Thermocouples made with this new mineral insulation material have demonstrated greater signal stability and three to four times longer life when compared to similar sensors made with MgO (3). Experimental data demonstrating improved life and signal stability has been previously published in Reference 3.

THE VIRTUAL JUNCTION TEST

Because Type K thermocouples are so important in industry and by far the most common thermocouples used for high temperature measurement in industry and because they often operate in the ranges where MgO insulation begins to weaken, they were chosen for this experiment. The same results should be seen for other types of thermocouples such as Type N or other non-standard pairs that can operate in this temperature range since it is the insulation that is compared in this test.

Virtual Junction Test - MI-Dry vs. MgO (See FIG. 2)

- 2 – 10 foot long, 1/8in OD, Type K Thermocouples, Inconel 600 Sheath, One with MgO insulation and one with MI-Dry insulation
- 2 – high temperature ovens, one for the thermocouple tips and one for the mid-section
- 2 – reference sensors, one for each of the two ovens (Note: As shown in FIG. 2, the two reference sensors do not pass through the mid-section oven but independently measure the temperature inside each oven)

Virtual Junction Error Test Conditions:

- Bring the thermocouple tips to about 1500F and hold them there
- Bring thermocouple mid-sections to about 2000F and hold them there

Results: (See FIG. 3)

1. Virtual Junction Error was apparent in the MgO sensor almost right away
2. After ~ 100 hours
   The MgO sensor was reading ~ 10% (170°F) high.
   The MI-Dry sensor was reading correctly.
3. After ~ 400 hours (See FIG. 4)
   The MgO sensor was reading ~ 19% (290°F) high.
   The MI-Dry sensor was reading correctly.
The sensors were all allowed to cool to ambient temperature and the test repeated. This time the 300 degree F error in the MgO sensor reappeared right away indicating that the effect was permanent. Similar virtual junction tests have been performed with $\frac{1}{4}''$ OD sensors with the same results.

CONCLUSIONS

A new dielectric mineral insulation has been developed that provides superior performance over MgO in thermocouple construction. It can reduce or eliminate virtual junction error. This dielectric, called Mi-Dry™, has several advantages over MgO:

- Less hygroscopic
- Slows, and/or prevents contaminating ion movement through the dielectric
- Increased electrical insulation properties at higher temperatures

These advantages can reduce or eliminate the risk of temperature uncertainties caused by Virtual Junction Error in Type K sensors for furnace and turbine engine applications.

Large measurement errors due to virtual junction in thermocouples made with MgO have been demonstrated for certain conditions (See FIG. 4). The observant operator might detect errors of this magnitude – possibly by comparison to other measurements or observations. Nonetheless, the desired temperature measurement is rendered useless. A more serious problem can occur when the errors are small enough not to be obvious and the measurements are depended upon for process control. Costly and perhaps catastrophic results can ensue.

REFERENCES

### TABLE 1 – INSULATION RESISTANCE MEASUREMENTS

**Comparison of MI-Dry and MgO Insulation Resistance**

(1/4" Type K sensors, Inconel 600 sheath @ 1200 C)

<table>
<thead>
<tr>
<th>Test 1 (2200 hrs)</th>
<th>Test 2 (1300 hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ExL (MI-Dry) Sensors</strong></td>
<td><strong>ExL (MI-Dry) Sensors</strong></td>
</tr>
<tr>
<td>AT-MD20006</td>
<td>17,956</td>
</tr>
<tr>
<td>AT-MD20007</td>
<td>19,311</td>
</tr>
<tr>
<td>AT-MD20008</td>
<td>16,362</td>
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<tr>
<td><strong>Average</strong></td>
<td>17,876</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>MgO Sensors</strong></th>
<th><strong>Ohm</strong></th>
<th><strong>MgO Sensors</strong></th>
<th><strong>Ohm</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Company O</td>
<td>646</td>
<td>Company M Sample A</td>
<td>344</td>
</tr>
<tr>
<td>Company W</td>
<td>212</td>
<td>Company M Sample B</td>
<td>361</td>
</tr>
<tr>
<td>Company H</td>
<td>41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Company B</td>
<td>593</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>373</td>
<td><strong>Average</strong></td>
<td>353</td>
</tr>
</tbody>
</table>

**Ratio MI-Dry / MgO**

- Test 1: 48
- Test 2: 61

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**FIG. 1 – INSULATION RESISTANCE VS TEMPERATURE**

1/8” OD, Type K Thermocouples, Inconel 600 Sheath

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FIG. 2 – EXPERIMENTAL APPARATUS

1/8" OD, Type K Thermocouples, Inconel 600 Sheath

FIG. 3 – THERMOCOUPLE READOUTS VS. TIME (VIRTUAL JUNCTION CONDITIONS)
FIG 4. – MAGNITUDE OF ERRORS UNDER VIRTUAL JUNCTION CONDITIONS