You've re-invented what? Yes, that's right, the Type K thermocouple

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ABSTRACT

New Type K, N and J thermocouples are now being manufactured that have significantly longer life, improved signal stability and are drop-in replacements for existing Type K, N and J thermocouples. This is the result of the development of a new dielectric mineral insulation material that replaces Magnesium Oxide (MgO), the insulating material used by all current manufacturers. In many industrial processes, accurate measurement of temperatures is critical to product quality, safety, and ultimately, profitability. Although thermocouples have been used for many years, users are always looking for ways to improve thermocouple performance, both in accuracy and length of service. Many improvements have been made in thermocouple wire and sheath materials, but the primary insulant material used in the manufacture of thermocouples, magnesium oxide (MgO) has remained the same. The two primary concerns with MgO are that it absorbs moisture and that it's insulation resistance drops dramatically as the thermocouple reaches operating temperatures. The absorption of moisture in a thermocouple leads to green rot and early failure and also has negative consequences on the insulation resistance. It is not uncommon to see insulation resistance drop from one Gig-ohm at ambient temperature to less than 100 ohms at 1100 degrees C. Recently a new dielectric insulation material has been developed that provides significantly higher resistance to moisture absorption and maintains much higher insulation resistance values at operating temperatures. This new material is called MI-Dry™. Comparison performance data between MgO and MI-Dry will be presented. A graphic example of erroneous readings due to virtual junction errors from the failure of MgO showing that this does not happen with the new insulant material will also be presented. Thermocouples made with this new material are already saving thousands of dollars in furnaces and reactors in Steel and Chemicals plants and will have a great impact on improving instrumentation and control of other industrial processes such as refineries, electric utilities and other manufacturing operations where reliable high temperature measurements are needed.

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. If 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. 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^{TM}.

The effectiveness of an electrical insulating material is usually determined by measuring its resistance. In thermocouples this is called Insulation Resistance (IR). An inverse relationship of resistance to temperature is a common electrical property of most materials. Therefore the IR of a thermocouple drops as it is heated to higher temperature. Loss of IR can cause failure of the thermocouple and can be caused 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 can be 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 (Nicholas, J.V and White, 1994). This makes it very important to have materials with consistent composition from one end to the other so that the same signal is generated regardless of the positioning of the temperature profile. It is also essential that the insulating material surrounding the wires in a thermocouple protect them from contamination and does not allow 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 (Anderson, R.L., et.al., 1982). 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. Blocking the migration of impurities is a primary function of a good insulant in addition to providing electrical insulation. 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 inside a thermocouple decreases its insulation resistance, causes chemical changes in the material and aids in the transport of ions within the thermocouple. Moisture also contributes to corrosion of some of the alloy materials used in thermocouples – another cause of inhomogeneity. 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 be compromised.

Virtual junction error, which will be discussed later, is sometimes mistaken for decalibration due to inhomogeneity. It is a different process, but is also a result of insulation breakdown.

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, which is called MI-Dry™, is much less hygroscopic than MgO and has better electrical resistance properties in thermocouple service than MgO. It is fabricated into thermocouple cable in exactly the same manner as MgO. MI-Dry not only has superior electrical resistance, but it blocks the diffusion of trace elements to the thermoelement wires. Because it is much less hygroscopic than MgO, MI-Dry 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 2000ºC, whereas MgO will react with most metals above 480ºC. It exhibits negligible reaction with conducting wires or other materials up to 1300ºC. Insulation Resistance (IR), measured by a simple ohm-meter from wire to sheath, is commonly used to check for thermocouple integrity. Higher IR is desirable. TABLE 1 summarizes IR measurements from two experiments where ¼" OD Type K thermocouples made with MI-Dry and MgO were compared at 1200 C. In Test 1 three MI-Dry Thermocouples averaged 17,876 ohm vs. 373 ohm average of four comparable MgO thermocouples from four major manufacturers. In Test 2, two Mi-Dry thermocouples averaged 21,644 ohm vs. 353 ohm average for two thermocouples from a 5th major manufacturer. The IR of thermocouples made with MI-Dry thermocouples was about 50 times that of the MgO thermocouples.

TABLE 1 – INSULATION RESISTANCE MEASUREMENTS

Comparison of MI-Dry and MgO Insulation Resistance

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

Test 1 (2200 hrs)		**Test 2 (1300 hrs)**	
ExL (MI-Dry) Sensors	Ohm	ExL (MI-Dry) Sensors	Ohm
AT-MD20006	17,956	MI-DRY sample A	22,254
AT-MD20007	19,311	MI-DRY sample B	21,034
AT-MD20008	16,362		
Average	17,876	Average	21,644
MgO Sensors	Ohm	MgO Sensors	Ohm
Company O	646	Company M Sample A	344
Company W	212	Company M Sample B	361
Company H	41		
Company B	593		
Average	373	Average	353
Ratio MI-Dry / MgO	**48**	**Ratio MI-Dry / MgO**	**61**

In another experiment, Insulation Resistance was measured at various temperatures for comparable 1/8" OD Type K thermocouples manufactured with MI-Dry and MgO. As shown in

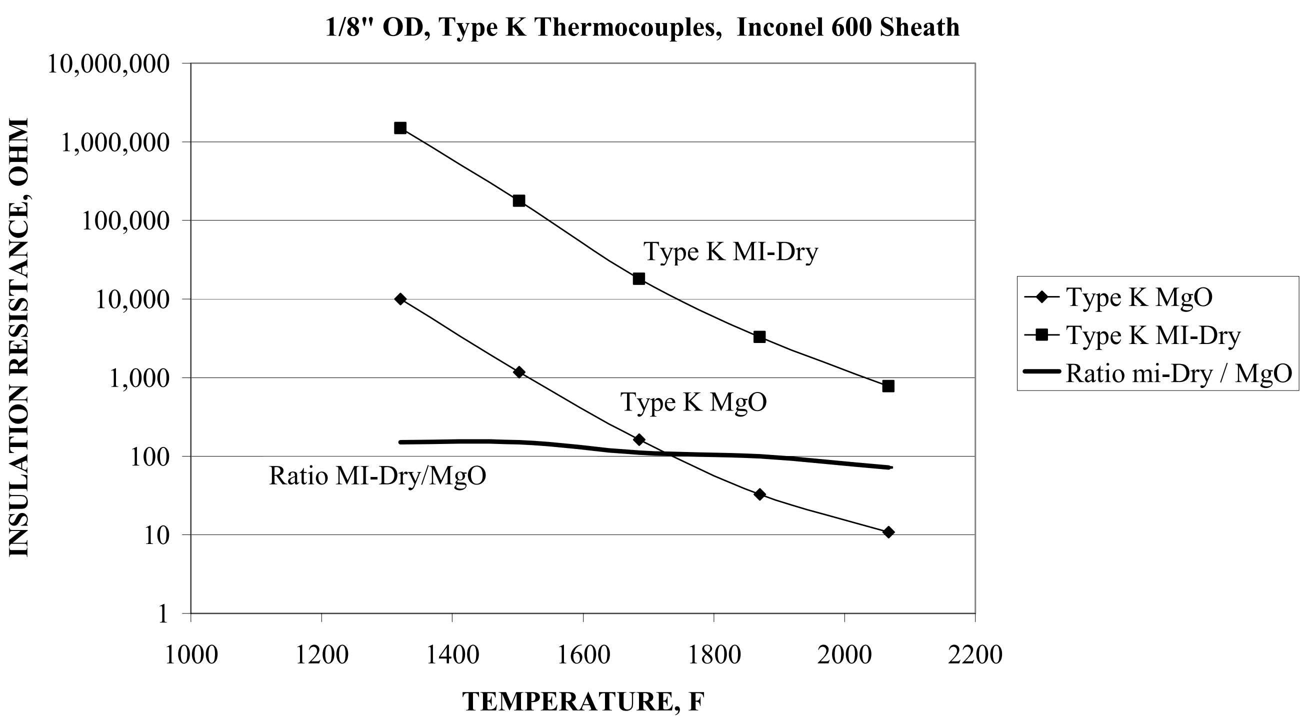

FIGURE 1 – INSULATION RESISTANCE VS TEMPERATURE

FIGURE 1, MI-Dry Insulation resistance was approximately 100 times greater over the entire range. Note that the IR scale is a log scale. Thermocouples made with the new MI-Dry insulation material have demonstrated reduced de-calibration, greater signal stability and up to three to four times longer life when compared to similar thermocouples made with MgO (Barberree, D.A., 2002). While Insulation Resistance of thermocouples is a function of geometry and temperature as well as the insulant, geometrically similar thermocouples fabricated with MI-Dry™ consistently exhibit 50-100 times higher insulation resistance than those manufactured with MgO. This property reduces or prevents shunting and virtual junction errors.

VIRTUAL JUNCTION ERRORS

The ASTM Manual on The Use of Thermocouples in Temperature Measurement (ASTM, 1993) 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 –400F to as high as 2500F (ASTM, 1997). 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 read outs because the thermocouple is effectively shortened and begins measuring the temperature gradients from a point different than the tip.

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 simple Virtual Junction Test. The same results should be seen for other thermocouple types such as Type N or other wire pairs that can operate in this temperature range since it is the insulation that is compared in this experiment. FIGURE 2 illustrates the test in which two – 10

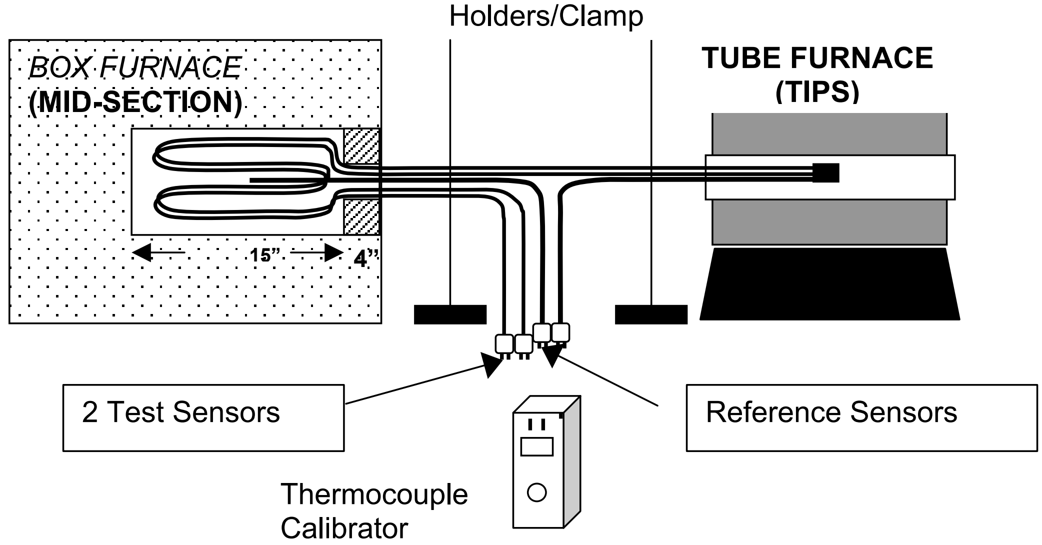

FIGURE 2 – EXPERIMENTAL APPARATUS

foot long, 1/8" OD, Type K Thermocouples, Inconel 600 Sheath - one with MgO insulation and one with MI-Dry insulation were compared. Two high temperature ovens, one for the

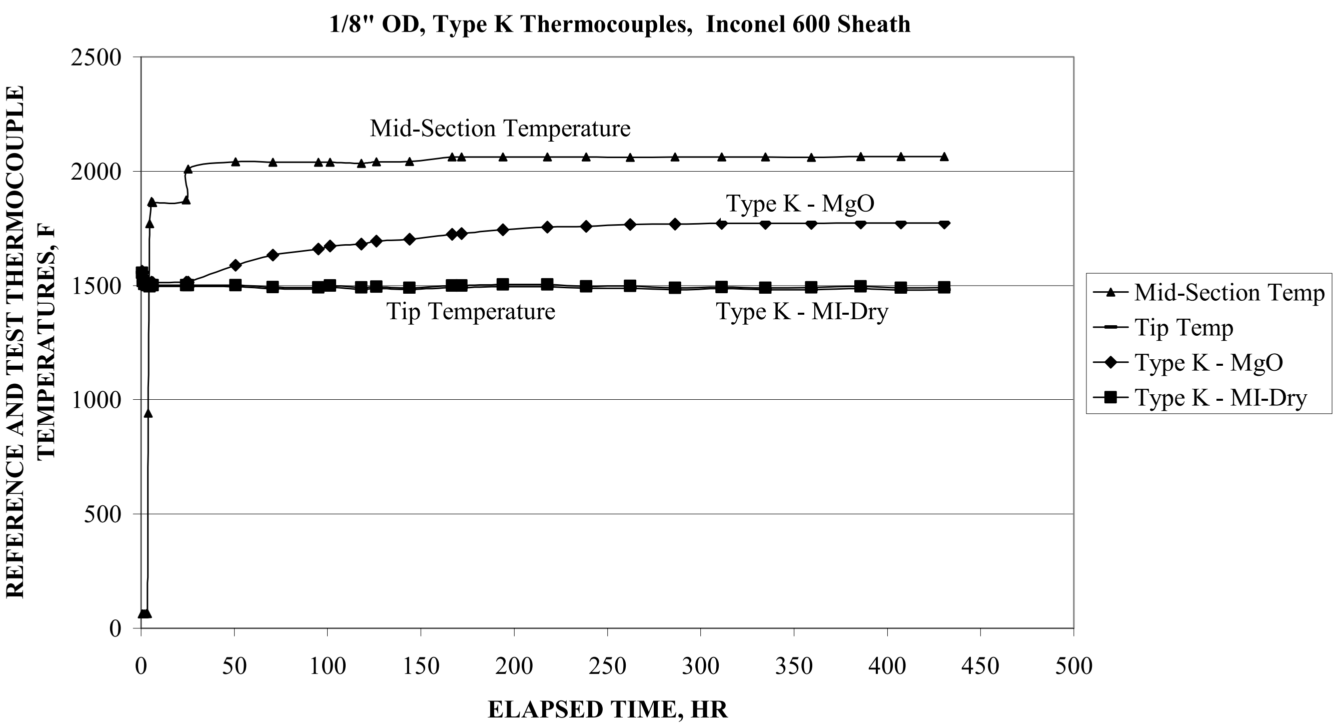

FIGURE 3 – THERMOCOUPLE READOUTS VS. TIME (VIRTUAL JUNCTION CONDITIONS)

thermocouple tips and one for the mid-section and two reference sensors, one for each of the two ovens were employed.

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

The following results are shown in FIGURE 3.

1. Virtual Junction Error was apparent in the MgO Thermocouple almost right away
2. After ~ 100 hours
   The MgO sensor was reading ~ 10% (170ºF) high.
   The MI-Dry sensor was reading correctly.
3. After ~ 400 hours
   The MgO sensor was reading ~ 19% (290ºF) high.
   The MI-Dry sensor was reading correctly.

The MgO thermocouple continues to read and give a strong signal even though the temperature is incorrect by nearly 300 deg F. FIGURE 4 better illustrates the magnitude if these erroneous readings.

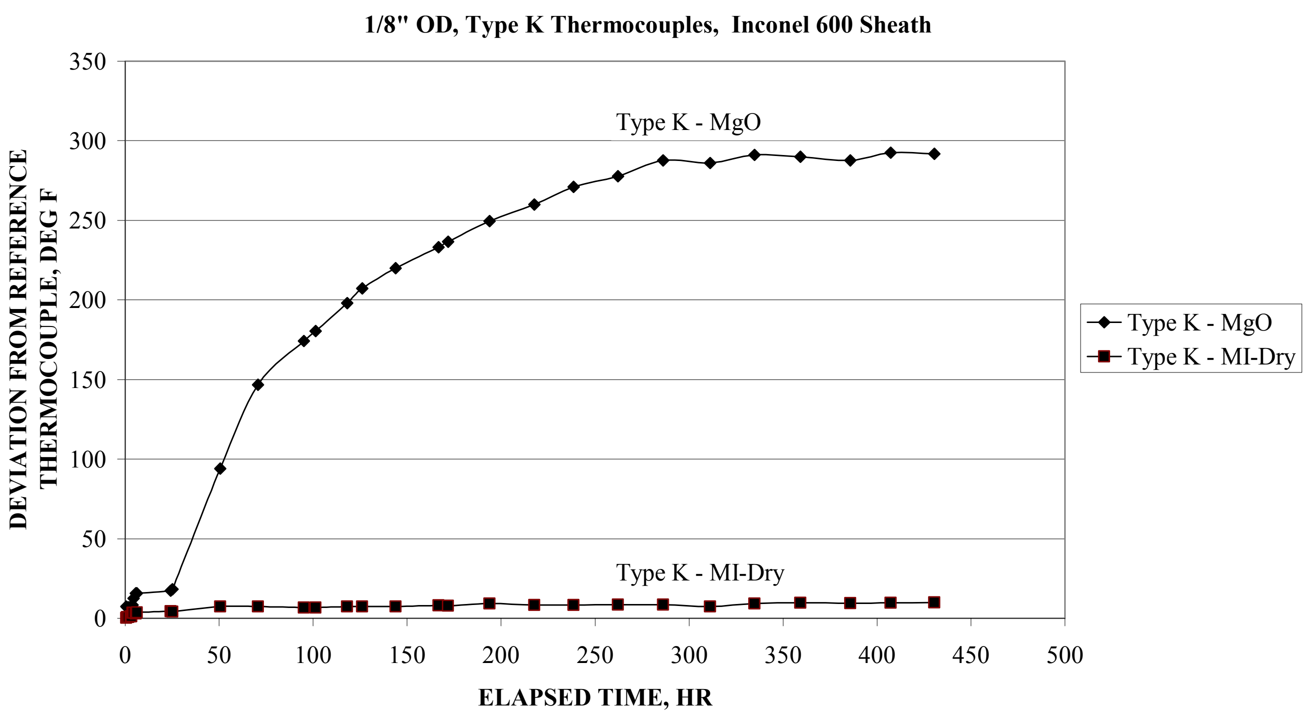

FIGURE 4 – MAGNITUDE OF ERRORS UNDER VIRTUAL JUNCTION CONDITIONS

The sensors were allowed to cool to ambient temperature and the test was repeated. This time the nearly 300 degree F error in the MgO sensor reappeared right away indicating that the effect was permanent. Similar virtual junction tests have also been performed with ¼" 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 thermocouple de-calibration leading to longer life and can also 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. 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. Serious problems can occur when these errors go un-noticed or are small enough not to be obvious and the measurements are depended upon for process control. Costly and perhaps catastrophic results can ensue.

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