A Thermocouple Self-Heating Test For Leak Detection In A High Level Liquid Waste (HLLW) Storage Tank

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Abstract

Following the discovery of an internal leak in one of three ¼ inch diameter re-entrant thermo-well tubes in an HLLW storage tank, a simple and non-invasive liquid detection method which consists of monitoring the temperature of the thermocouple inside the thermo-well before and after a brief period of thermocouple resistive heating, has been developed. The heat transfer rate, and consequently the temperature trend, is markedly different depending on whether or not liquid is present inside the thermo-well. Application of this method to determine the state of the remaining two thermo-wells of the storage tank has resulted in a significant reduction in uncertainty for controlling radiological risks and for developing and deploying investigation and remediation procedures. The method continues to be used regularly to monitor the state of one of the thermo-wells to ensure continuing safety for tank operations.

1. Introduction

Three thermocouples at different heights are used to monitor the temperature of the highly radioactive liquid inside an HLLW storage tank at Chalk River Laboratories. The thermocouples are inserted into re-entrant ¼-inch inside-diameter stainless steel tubes or thermo-wells, labelled according to height, with no. 1 being the lowest in height (i.e., deepest inside the liquid) and no. 3 being the highest (i.e., shallowest). Unexpected radioactive contamination was found on thermocouple no. 2 during a routine preventive maintenance replacement procedure in 2006, implying that an internal leak had developed in the mid-length thermo-well, possibly as a result of corrosion after some 20 years service in the acidic, ~70 °C, high radiation environment [1]. After taking immediate compensatory actions to place the HLLW tank in a safe state, there was an immediate need to determine the extent of tank condition degradation, beginning with an evaluation of the remaining two thermo-wells.

Extraction of the remaining two thermocouples required development of non-routine procedures and special equipment to mitigate the radiological risks from possible contamination. A non-invasive test for the presence of liquid inside the thermo-wells was therefore desirable. To be useful, the test needed to be simple and safe, use easily available equipment, and provide an unambiguous result. The test described here, based on measuring the temperature rise following resistive "self-heating" of the thermocouple already deployed inside the thermo-wells, was developed in a short time frame to meet these requirements.

2. Approach

2.1 Thermocouples

The HLLW storage tank is located in an underground, shielded vault. Mineral insulated, 1/8-inch diameter, J-type, grounded thermocouples with stainless steel sheaths are deployed inside the tank thermo-wells. The thermocouples are inserted vertically downwards from the floor above the tank vault. Thermocouple nos. 1, 2, and 3 are respectively 15.5 ft, 13.5 ft, and 11.5 ft in total length, with approximately 7.5 ft outside the tank, and the remainder of their length inside the storage tank thermo-wells.

As depicted in Figure 1, the electrical resistances of the thermocouple wires can be inferred from measurements as follows. The resistance measured from the negative (constantan) lead to the stainless steel sheath at the top end of thermocouple no. 1 is 8.8 ohms, and from the positive (iron) lead to the sheath is 4.2 ohms. However, the resistance measured between the positive and negative leads is 10.4 ohms. The resistances of thermocouple no. 1 conductors can then be resolved as 7.5 ohms for the negative (constantan) wire, 2.9 ohms for the positive (iron) wire, and 1.3 ohms for the stainless steel sheath. The resistances of the thermocouple conductors are proportional to length.

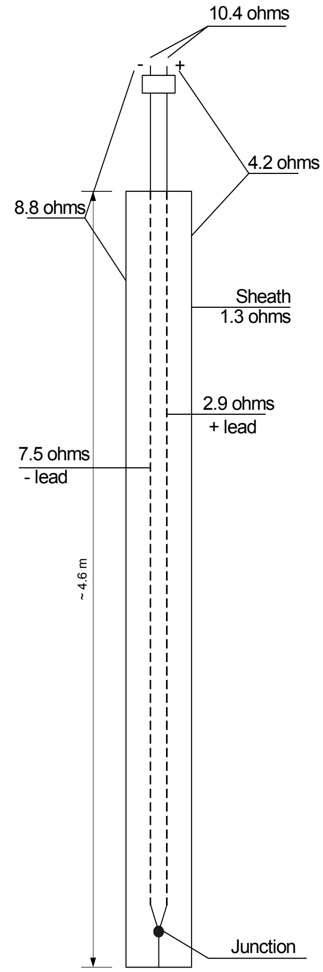

Figure 1. Thermocouple No.1

2.2 Principle

The principle of the test is to measure the thermal conductance or heat transfer rate between the thermocouple junction and the walls of the thermo-well. Incidental contact of the thermocouple with the inside walls of the cylindrical thermo-well, in dry air, gives rise to a relatively low thermal conductance, while the presence of liquid around the thermocouple tip leads to a relatively large thermal conductance.

To measure the thermal conductance, electrical current is passed through the thermocouple conductors, resulting in resistive "self-heating" of the conductors and of the temperature-sensing junction. The temperature of the thermocouple junction is monitored immediately following the passage of current. When the thermo-well is dry, the injection of heat via resistive self-heating causes the temperature of the thermocouple junction to rise significantly. When liquid is present, the heat injected into the thermocouple by self-heating is efficiently conducted into the thermal sink provided by the thermo-well, and the temperature rise of the thermocouple junction is very small compared to the temperature rise when the thermocouple is dry.

Laboratory tests, using a spare thermocouple and readily available measuring equipment, determined that a 1 Amp current flowing for 1 minute between the negative (constantan) terminal and the sheath was sufficient to raise the thermocouple junction temperature by approximately 1.5 °C, when the thermo-well was dry. Laboratory tests also showed that in a dry thermo-well, attempts to increase thermal contact by mechanical means, such as application of pressure or the presence of particulates, did not significantly affect the temperature rise of 1.5 °C. The presence of moisture or water vapour in the thermo-well caused a decrease in the observed temperature rise. When liquid was present at the thermo-well tip, the temperature rise was found to be less than 0.3 °C in all cases. The laboratory tests thus demonstrated that this test would provide unambiguous results.

The theoretical calculation in Appendix A predicts a temperature rise of about 6.3 °C for a dry thermo-well where the thermal conductance is assumed to be provided by dry air only, and 0.5 °C when water is present in the thermo-well. The laboratory observations reasonably match this calculation, because the model used for calculation does not consider the heat absorbed by the ambient air or water, and ignores heat transfer by convection and by incidental metal-to-metal contact, all of which contribute to a lower temperature rise. From this point of view, the experiments confirm that the calculation is rational.

3. Application

The thermocouple self-heating liquid detection test, as described, was applied to the three thermocouples in the HLLW storage tank. At the time of application, thermo-well no. 2 was known to have had liquid present in it, but the state of dryness of thermo-well nos. 1 and 3 was unknown. The equipment, procedure, and results are described below.

3.1 Equipment and Procedure

As shown in Figure 2, three pieces of equipment were deployed for the test. A standard regulated power supply provided 1Ampere current for resistively heating the thermocouple on demand. An OMEGA Model DP80 thermocouple transmitter with cold junction compensation and a GPIB link was used to take temperature measurements. A laptop computer running a LabView program controlled the DP80 transmitter and recorded the temperature data.

A procedure, as follows, was developed based on the above equipment configuration. The thermocouple connector was disconnected from the normal monitoring electronics panel of the storage tank, and connected to thermocouple leads running to the OMEGA DP80 temperature transmitter, to take a baseline reading. After obtaining the baseline reading, the tester manually disconnected the thermocouple connector from the DP80 temperature monitor, and attached two alligator clip-type leads from the 1 Ampere power supply to (a) the constantan thermocouple lead (current in) and (b) the thermocouple sheath (current return and ground). The power supply, previously adjusted to supply 1 Ampere current, was manually turned on and off for a hand-timed interval of 1 minute. Immediately after the power supply was turned off, the tester manually removed the power supply alligator clip-type leads, and re-connected the thermocouple to the OMEGA DP80 temperature transmitter. The LabView program running in the computer recorded the temperature from beginning to the end of the test at 5 seconds intervals.

The thermocouple was allowed to cool back to ambient temperature for 5 to 10 minutes. The test procedure was repeated for a total of 3 self-heating cycles per thermocouple.

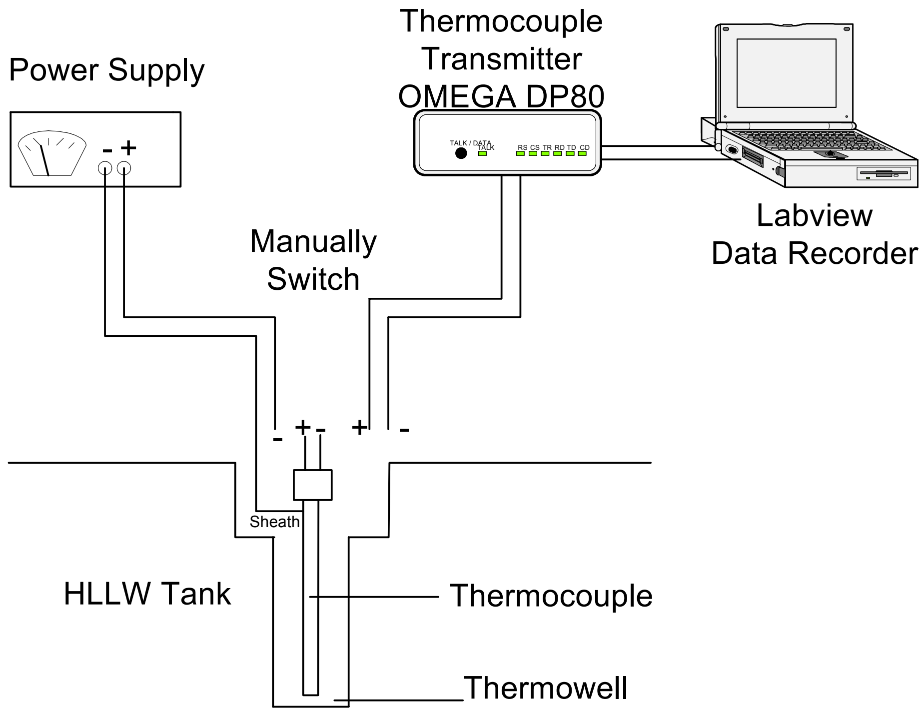

Figure 2 Testing Equipment and Configuration

3.2 Data and Results

Figure 3 shows the recorded temperatures vs. the time-of-day for each of the three thermocouples. In Figure 3, gaps in the temperature trend indicate the intervals during which the thermocouple leads were disconnected from the temperature transmitter and connected to the regulated power supply for thermocouple "self-heating". Short-term variations in temperature immediately following the heating intervals are evident, especially in Figure 3 (a), and are discussed in more detail below. The observed long-term trends in temperature are caused by variations in the room, i.e., thermocouple cold junction temperature, as a result of the imperfect cold junction compensation provided by the OMEGA DP80 unit.

Figure 4 shows the same data as Figure 3, but is plotted to show the change in temperature as a function of time immediately following the heating interval. In the plot for each thermocouple, the unconnected symbols show the observations and the solid line is the average of the three heating cycles.

Thermocouple no. 1 showed an average temperature rise of 1.2 °C and a temperature decay time constant of approximately 80 s. Clearly, there was no liquid present, and therefore no leak in thermo-well no. 1.

Thermocouple no. 2 showed an average temperature rise less than 0.2 °C, and a very short temperature decay time constant, consistent with the expectation for presence of liquid. Radioactive contamination of HLLW composition had been found on the thermocouple previously removed from thermo-well no. 2, indicating that liquid had been present in thermo-well no. 2 at some time prior to this test. Consequently, the continued presence of liquid in this thermo-well was not entirely unexpected. This test result confirmed that there was a continuing leak inside this thermo-well.

Thermocouple no. 3 showed an average temperature rise less than 0.3 °C, and a short temperature decay time constant. Both these characteristics were similar to the response of thermocouple no. 2, as opposed to the response of thermocouple no. 1. Based on this response, thermo-well no. 3 was declared flooded. To confirm that the small temperature rise, i.e., large thermal conductivity, was indeed caused by the presence of liquid and not by some other mechanism, the test on thermocouple no. 3 was repeated after moving the thermocouple slightly. The repeat test unambiguously demonstrated that liquid was present in thermo-well no. 3.

4. Discussion and Conclusion

The results of the thermocouple self-heating test removed the uncertainty in knowing whether or not thermo-wells no. 1, 2, and 3 had liquid present in them. The test showed that there was minimal risk of radioactive contamination in removing thermocouple no. 1, and a relatively high radiological risk in removing thermocouple no. 3. Consequently, procedures, equipment, and radiological work plans developed for inspection, investigations, and remediation of the leaking thermo-wells were first tried out and perfected in thermo-well no. 1. Subsequent extraction of the thermocouples and inspections of thermo-well nos. 2 and 3 confirmed that they were flooded, as per the results of the thermocouple self-heating tests.

Temporary plugs have now been installed in thermo-well nos. 2 and 3 and operations on the HLLW storage tank have been resumed. The thermocouple self-heating test is currently performed routinely on thermo-well no. 1 to confirm that it is not leaking, and thus safe for operations. The self-heating tests are expected to continue until the thermo-wells are permanently repaired.

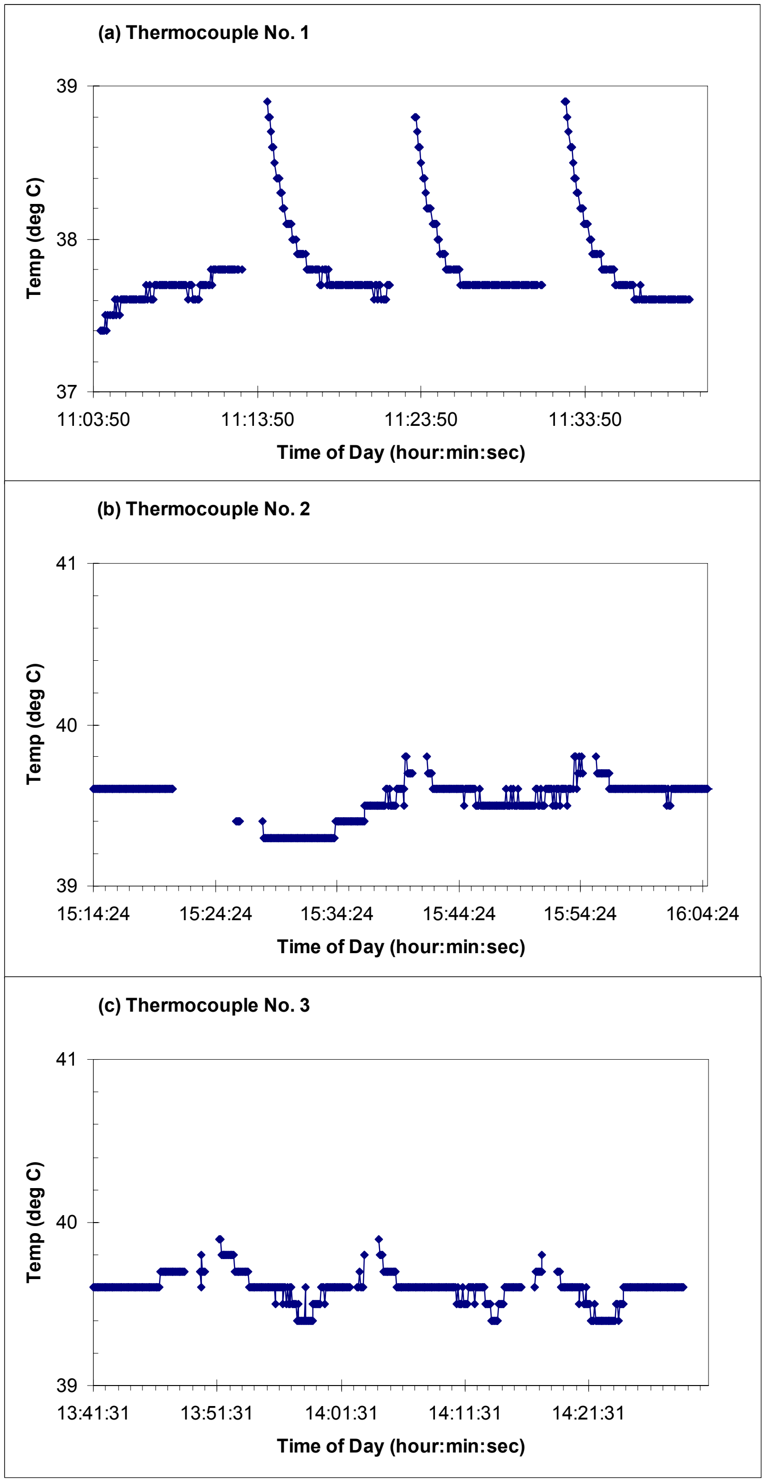

Figure 3 Temperature vs. time from self-heating test for (a) Thermocouple no. 1, (b) Thermocouple no. 2, and (c) Thermocouple no. 3. Gaps in the line joining the data points indicate self-heating intervals.

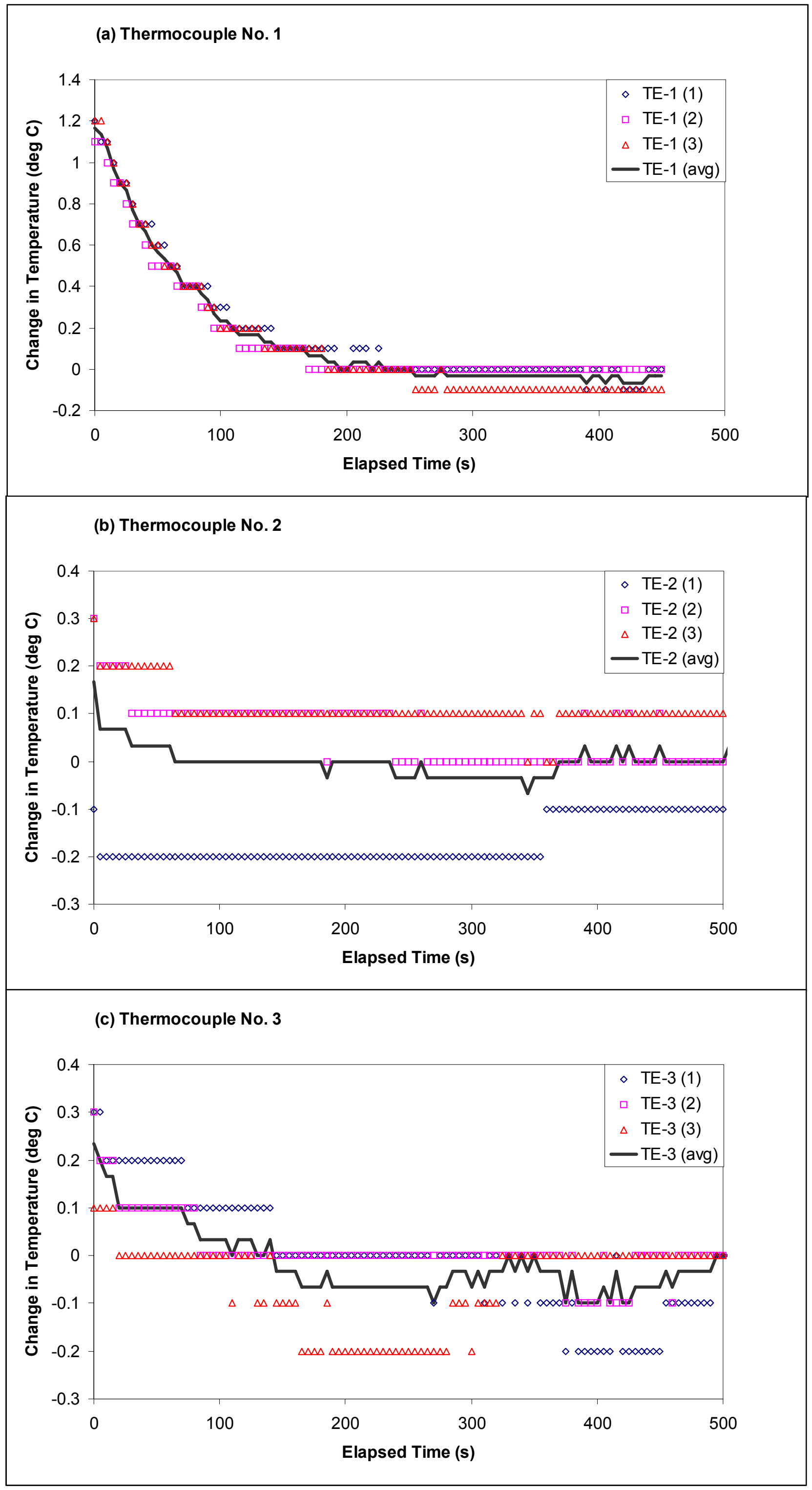

Figure 4 Change in Temperature vs. time after self-heating for (a) Thermocouple no. 1, (b) Thermocouple no. 2, and (c) Thermocouple no. 3. Data from each trial, x, for each thermocouple, n, is labeled as TE-n (x). A solid line shows the average of all three trials.

5. Acknowledgements

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6. References

[1] B. Sur, S. Yue, and A. Thekkevarriam, "Radiation Exposure Rate and Liquid Level Measurement Inside a High Level Liquid Waste (HLLW) Storage Tank", *Proc. 28th Annual Conference of the Canadian Nuclear Society,* 2007.

APPENDIX A: CALCULATION OF TEMPERATURE RISE CAUSED BY HEAT TRANSFER IN THERMOWELL

The thermocouple is 1/8" in diameter and located inside the ¼" inner diameter steel thermo-well. The gap between thermo-well wall and thermocouple is about 2 mm, as demonstrated in Figure 5. To simplify the calculation, we reasonably assume that the heat is transferred mainly by conduction and ignore convective heat transfer.

Using the following symbols:

- H: Heat transfer rate (from thermocouple to thermowell)
- k: Thermal conductivity of air or liquid around the thermocouple
- T: Temperature of thermocouple
- T_w: Temperature of thermo-well (constant)
- T_0: Thermocouple temperature after being heated up
- A: Area of the thermocouple surface
- L: The distance of transfer path (about 2 mm here)
- t: Time
- Q: Internal energy of the thermocouple
- m: Mass of the thermocouple
- c: Specific heat of the thermocouple
- P_e: Resistive heat produced by electrical power

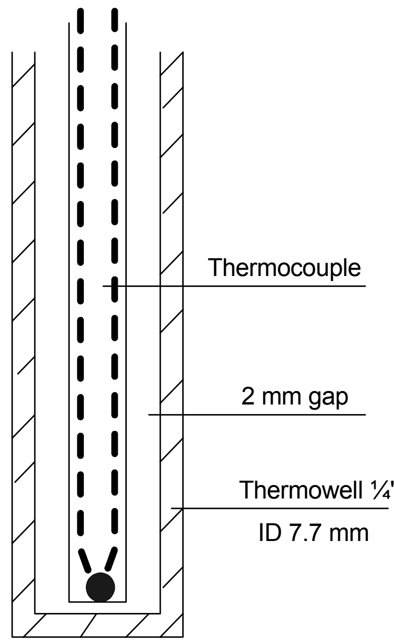

Figure 5 Thermowell

The rate of heat transfer by conduction is:

$$H = kA\,(T - T_w)/L \qquad (1)$$

When there is no heat input the temperature decay of the thermocouple depends on the heat transfer rate as follows:

$$H = -\,d(Q)/dt \quad = \quad -\,mc\,d(T)/dt \qquad (2)$$

Solving equation (1) and (2), the thermocouple temperature during cooling down is:

$$T = T_w + (T_0 - T_w)\,exp(-t/\tau) \qquad (3)$$

With time constant $\tau = mcL/kA$,

$\tau_{air} = 80\ seconds$ (experimental value with thermo-well being dry)

$$\begin{aligned}\tau_{water} &= \tau_{air}\,K_{air}\ /\,K_{water}\\ &= 80 * 0.026\ J/(s.m.c) / 0.600\ J/(s.m.c)\\ &= 3.5\ seconds \quad \ll \tau_{air}.\end{aligned}$$

Therefore the time constant of temperature decay depends on whether or not liquid is present in the thermo-well.

During thermocouple self-heating,

$H = P_e - d(Q) / dt \quad = \quad P_e - m\, c\, d(T) / dt$ (4)

Solving equation (1) and (4), the thermocouple temperature during self-heating is:

$T = T_w + P_e L/(kA)(1 – exp(-kAt/mcL))$ (5)

Or

$\Delta T = (T - T_{w)} = P_e L/(kA)(1 – exp(-t/\tau))$ (6)

The temperature of thermocouple starts at Tw, increases and saturates exponentially at a temperature $Tw + P_e L/(kA)$ *when* $t \rightarrow \propto$.

Using the bottom 30 mm of the thermocouple to calculate the temperature change,

$P_e = I^2 R = 1.0^2 * (7.5\ ohms / 4600mm)\ 30\ mm = 0.048\ watt$

$A = 3.14 * 0.0032 * 0.03 = 0.0003\ m^2$

$K_{air} = 0.026\ J/(s.m.c)$ and $K_{water} = 0.600\ J/(s.m.c)$

Inserting values for P_e, A, K_{air}, and K_{water} in (6):

$\Delta T_{air} = 0.048*0.002/(0.026*0.0003)(1 – exp(-t/\tau_{air}))$
$= 12\ (1 - exp(-t/\tau_{air}))$

$\Delta T_{water} = 0.047*0.002/(0.60*0.0003)(1 – exp(-t/3.5))$
$= 0.5 * (1 – exp(-t/3.5))$

After 1 minute (60 seconds) resistive self-heating, the thermocouple temperature increase is calculated as:

$\Delta T_{air} = 12\ (1 – exp\ (-60/80)) \quad = \quad 6.3\ ^oC$
$\Delta T_{water} = 0.5 * (1 – exp(-60/3.5)) \quad = 0.5\ ^oC \qquad << \qquad \Delta T_{air}$

Therefore, the presence or absence of liquid can be determined on the basis of the temperature rise after passing electrical current through thermocouple for one minute.

In conclusion two characteristics of the thermocouple temperature measurements are useful to determine if liquid is present in the thermo-well. One is the time constant of temperature decay, the other is the temperature change after self-heating by a 1 ampere current for 1 minute. The calculated temperature change does not equal the experimental value, because the model used for calculation does not consider the heat absorbed by the surrounding air or liquid, or the heat transfer via convection and via incidental metal-to-metal contact. However, these calculated numbers still provide a good reference for expectations from an actual test.