

STABILIZED METAL SHEATHED TYPE K AND E THERMOCOUPLES IMPROVE TURBINE EFFICIENCY

T.P. Wang, PhD, Consultant
D.P. Bediones, BS, Cal Lab Supervisor
Thermo Electric Co. Saddle Brook, N.J., U.S.A.

P. Swirla, CET
Thermo Electric Canada
Ontario, Canada

H.J. Henrikson, BS, P Eng., Production Supervisor
E.J. Janhunen, CET, Control Technologist
K. Bachalo, BS, P Eng., Senior Thermal Station Engineer
Ontario Hydro, Courtright, Ontario, Canada

KEYWORDS

Turbine, Efficiency, Stabilized, Metal Sheathed, Thermocouples

ABSTRACT

This paper describes the products and two year field tests up to 6000 hrs, which led to the adoption of stabilized metal sheathed Type K and E thermocouples for precision control of steam temperature at 538°C at the Lambton Generating Station of the Utility Company. Efficiency calculations demonstrated that the use of these stabilized metal sheathed thermocouples for the control of steam temperature could save \$200,000 per year in fuel cost for this generating station with four 500 megawatt units. This would translate to an annual savings of \$2,000,000, in fuel cost alone, for a large utility company with ten such stations. Fuel savings worldwide could reach over \$400,000,000 per year.

INTRODUCTION

In the dawn of deregulation of the utility industry, the company which can produce electricity at a lower cost will be ahead of the others. This paper contains the second set of data, resulting from the joint investigation of the Utility Company and the Supplier Company. Our previous joint paper (1) showed that standard Type K metal sheathed thermocouples were found to shift 5°C more positive after extensive use, while stabilized metal sheathed thermocouples were essentially unchanged after initial 90 days of field test at 538°C. It should be stated that, at the start, all thermocouple suppliers were contacted and advised of the requirement of initially meeting special limits and remaining within special limits after prolonged exposure to 600°C. All but one withdrew. For this paper, the field testing of stabilized metal sheathed Type K thermocouples was extended to 4,000 hours of actual operation at temperature. A group of stabilized Type E metal sheathed thermocouples was similarly tested to 6,000 hours. Neither of these thermocouples showed any significant shift in calibration. The field test results are presented after a brief description of the thermocouple setup at Lambton, a differentiation between standard and stabilized metal sheathed thermocouples, and the results of the 3200 hr. laboratory test at 538 °C of stabilized Type K and E thermocouples. The technical reason for the stability of these thermocouples is discussed prior to the annual fuel cost savings calculations. Lastly, justification for the utility industry to convert to stabilized metal sheathed thermocouples is provided.

Stabilized Thermocouple Testing And Application at Lambton

An extensive rehabilitation project was carried out at the generating station (four unit station having capacity of 500 MW each unit) in the early 1990's concentrating on Units 3 and 4. A significant amount of instrumentation was replaced with Smart transmitters in the field and the controls were replaced with a Distributed Control System (DCS). A few years prior to the rehabilitation project, the station process computer was replaced. An efficiency monitoring computer, called ECOS (Energy Conversion Optimizing System) was also installed shortly afterwards.

Process information provided via the ECOS system, allow the station staff to focus on the reliability and accuracy of instrumentation used for control and efficiency calculations. The differences between similar process variables, but from different sources (DCS and process computer), are easily compared using the ECOS system. The need for higher accuracy instrumentation paved the way for the station staff to get involved in the testing of stabilized thermocouples, which promised to provide more accurate and stabilized steam temperature measurement than standard thermocouples. In order to minimize fuel loss of a boiler-turbine generating unit, a precise temperature measurement is required. A series of tests were completed during the period of 1994-1996 which proved the stability of the stabilized thermocouples.

Boiler steam temperatures (both main steam and reheat steam outlet temperatures) are controlled at 538°C. This is the temperature at which the highest measurement accuracy is required. The stabilized thermocouples were purchased with a one point individual calibration at 538°C. The calibration results were used to adjust the process computer thermocouple constants and DCS configuration to match the characteristics of the thermocouple at this temperature of 538°C in order to achieve the highest accuracy. Fifteen to 25-foot long thermocouples were directly connected to the temperature transmitter which eliminated the normally used terminal block at the connection head. The steam temperature thermocouples used to provide information via the process computer to the ECOS monitoring system for efficiency calculations, were replaced with Type K stabilized material thermocouples. Thermocouple connections for these two systems (DCS and ECOS) and their digital information flow are shown in the diagram in Figure 1.

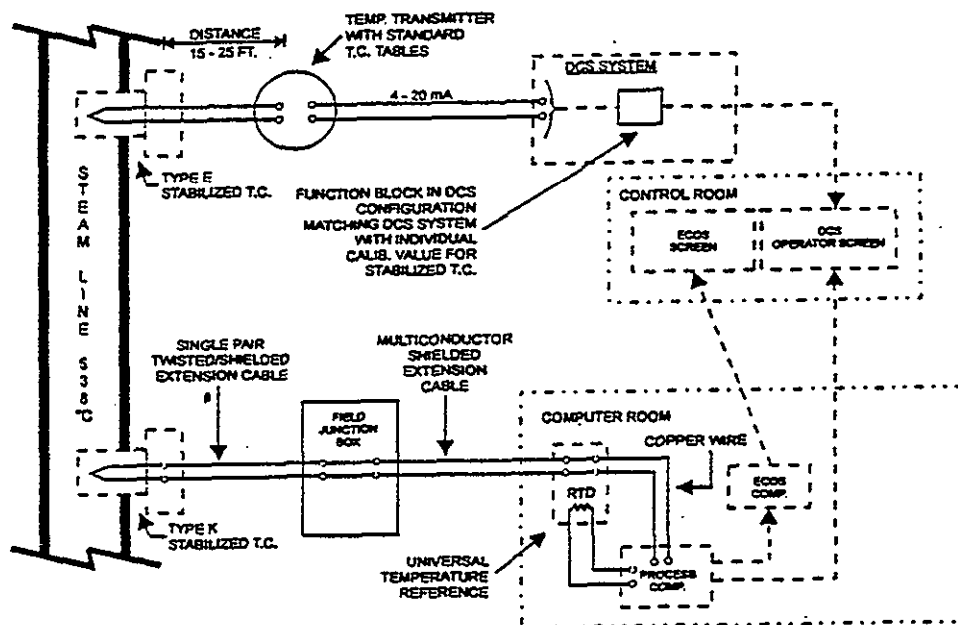


Fig. 1 Arrangement for Boiler Main Steam Temperature Measurement

System Accuracy Calculations.

The overall the system accuracy is calculated for a single input to the DCS system, using a Type E thermocouple at 538°C connected to a 4-20 mA temperature transmitter. An accuracy comparison is made between two models of a Smart temperature from the same manufacturer. Column A includes the transmitter model released in 1989 and is still being marketed. Column B includes a Smart temperature transmitter, released in 1996. The comparison shows how the overall system accuracy has improved from the improvement in transmitter accuracy.

The individual component accuracies are based on the manufacturer's published specifications. The higher transmitter ambient temperature (50°C) inside the boiler house represents a hot summer day while the lower ambient temperature (20°C) represents a cold winter day.

	Model A		Model B	
	at 20°C	at 50°C	at 20°C	at 50°C
Smart Temperature Transmitter				
Digital accuracy	±0.20°C	±0.20°C	±0.06°C	±0.06°C
Digital/Analog accuracy	±0.18°C	±0.18°C	±0.12°C	±0.12°C
Ambient temp. effect for 30°C increase				
Digital accuracy	—	±0.59°C	—	±0.16°C
Digital/Analog accuracy	—	±0.62°C	—	±0.26°C
Cold junction compensation accuracy	±0.5°C	±0.5°C	±0.3°C	±0.3°C
 (Total Transmitter Accuracy)	 (±0.56°C)	 (±1.03°C)	 (±0.32°C)	 (±0.45°C)
Field mounted calibrated thermocouple supplier's calibration sheet states that thermocouples were calibrated at 538°C with accuracy of	±0.63°C	±0.63°C	±0.63°C	±0.63°C
DCS system analog input accuracy	±0.6°C	±0.6°C	±0.6°C	±0.6°C
Total system accuracy	±1.03°C	±1.35°C	±0.93°C	±0.98°C

These total accuracies indicate that the Smart temperature transmitter is capable of passing on the improved accuracy of the stabilized thermocouples to the total benefit of the system.

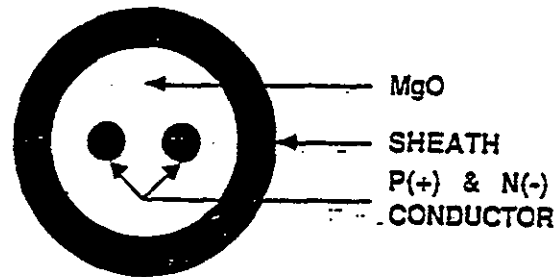
The process computer temperature measurement consists of the following components, which provide an error source contributing to the overall system accuracy:

Field-mounted calibrated thermocouple Type K supplier's calibration sheet states that thermocouples were calibrated at 538°C with accuracy of	±0.63°C
Field-run of extension cable (estimated)	±1.0°C
Computer analog input	±0.53°C
Cold end compensation accuracy	±0.53°C
Total system accuracy for process computer	±1.4°C

Type K And E Metal Sheathed Mineral Insulated Thermocouples

Most power plants try to hold the temperature of the main steam at 538°C, the most optimum operating temperature for steam turbines. For this application in a vibrational environment, Type K or E thermocouples are commonly used. As described in ASTM E230, the Type K (90 Ni/10 Cr vs 95 Ni/Si, Al) and the Type E (90 Ni/10 Cr vs 45 Ni/55 Cu) share the common positive thermoelement. The positive thermoelement of Type K and E, KP and EP, are exactly the same while their negative thermoelements KN and EN are different alloys (2).

Thermocouples in metal sheathed mineral insulated form, also commonly known as MI cables, offer flexibility and external protection of the thermoelements. These are important considerations in a vibrational environment. A cross sectional diagram of a metal sheathed mineral insulated thermocouple is shown in Fig. 2. The thermoelements P and N are embedded, most often, in MgO. Sometimes alumina is used. Depending on the specific application, the sheath material could be 304 or 316 stainless steel, Inconel 600 or other material deemed appropriate.



	TYPE K	TYPE E
+	KP 90 Ni/10 Cr	EP 90 Ni/10Cr
-	KN 95 Ni/Si, AL	EN 45 Ni/55Cu

Fig. 2 Cross Sectional View of Metal Sheathed Mineral Insulated Type K or Type E Thermocouples

Stabilized Metal Sheathed Type K and E Thermocouples

Stabilized Type K and E thermocouples meet the special calibration limits not only initially, but also after long exposure to a moderate temperature range of 400° to 600°C. These thermocouples were developed and specially processed at the Supplier Company. Supporting evidence of 3,000 hours laboratory test data at 538°C and field test data at the Utility Company are presented at the latter part of this paper.

Standard Type K and E thermocouples may shift out of calibration after relatively short exposure at the aging temperature range. The calibration change is attributed to the positive thermoelement, KP (EP). This phenomenon has been known and accepted. Now, a basic solution to the problem, stabilized metal sheathed Type K and E thermocouples, has been provided.

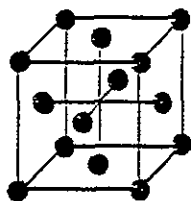
This solution is derived from understanding and harnessing the aging process, first in atomic and subsequently in macro scale. After the process is developed and the products are made, product differentiations are listed to segregate them from others.

Effect Of Aging On Thermal EMF And Atomic Structure Of KP (EP)

It has been reported that upon aging in the 400° to 600°C range, standard Type K thermocouples would change up to 5°C in the positive direction (3). The change is attributed to the positive thermoelement KP, as the EMF of KN is stable over this temperature range. The reason for this change is attributed to the short range ordering of KP upon aging in the above temperature range (4).

The atomic structure of KP is face centered cubic (f.c.c.), like other Ni/Cr alloys. The atomic sites, namely, the position available to be occupied by atoms in a cube of the face centered cubic structure, are shown as the shaded area in Fig. 3 (a). In the f.c.c. structure, there are a total of four atomic sites per unit cube, three face sites and one corner site. This is because each corner site is shared by eight adjacent unit cubes and each face site is only shared by the common face of two adjacent cubes. All thermocouple wire, unless otherwise stated, is supplied in the annealed condition, after rapid cooling down from the process temperature of about 1000°C. Under this condition, the nickel atoms (shown in white) and the chromium atoms (shown in black) are randomly distributed in the space lattice of the alloy. This structure is termed as the disordered structure.

Upon aging Ni/Cr alloys in the temperature range of 400° to 600°C, diffusion of the atoms takes place until equilibrium. When equilibrium is reached, the atoms are arranged in a periodic manner, with all the white nickel atoms at the center and all the black chromium atoms at the corner sites. The structure is said to be long range order if this condition exists over the entire atomic lattice of the Ni/Cr alloy. However, long range order is not possible for KP since the ratio of nickel atoms to chromium atoms is close to 10 to 1 instead of 3 to 1. As a result, part of the structure is ordered and the balance is disordered and this structure is termed as short range order. See Fig 3 (b). The change from the disordered structure to either long range or short range ordered structure is accompanied by significant changes in physical properties. Complete aging of KP results in a resistivity increase of 5% from the annealed state, accompanied by significant positive changes in thermal EMF (5). The lattice parameter, the distance between the center of the adjacent corner atoms of a 80 Ni/20Cr alloy, decreases until the completion of the aging process and remains essentially the same afterwards (6).

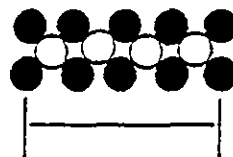


- Atomic Sites
- Chromium Atom
- Nickel Atom

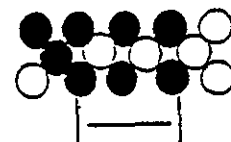
Fig. 3a Three Dimensional View of A Unit Cube of the f.c.c Structure



Disordered



Long Range Ordered



Short Range Ordered

Fig. 3b

Two Dimensional View of Structural Arrangement

Fig. 3 - Effect of Aging Between 400°C and 600°C on the Type K Positive Thermoelement (90Ni/10 Cr)

These stabilized Type K and E metal sheathed thermocouples were developed and specially processed at the Company, applying the above metal physics and other metallurgical principles. The difference between standard and stabilized thermocouples is described as follows.

Product Differentiation: Stabilized Vs Standard K & E Thermocouples

All thermocouples, whether standard or stabilized, must meet the initial calibration tolerance as specified in ASTM E230 in the as received condition. For Type K, the standard tolerance is $\pm 2.2^\circ\text{C}$ or $\pm 3/4\%$ of temperature, whichever is greater. The special or premium tolerance is $\pm 1.1^\circ\text{C}$ or $\pm 0.4\%$ of temperature, whichever is greater. Both cover the temperature range of 0 to 1260°C . For Type E, the standard tolerance is $\pm 1.7^\circ\text{C}$ or $\pm 0.5\%$ of temperature, whichever is greater. The special tolerance is $\pm 1^\circ\text{C}$ or $\pm 0.4\%$, whichever is greater. Both cover the temperature range of 0 to 870°C . At 538°C , the special tolerance for both the Type K and E thermocouple is $\pm 2.2^\circ\text{C}$. This applies to both standard unstabilized and stabilized thermocouples.

The difference between the two is that while both the standard and stabilized thermocouples are within special tolerance at the start, the stabilized thermocouples would remain in calibration over a long period of time, as proven by the laboratory and plant results which appear at the latter part of this paper. On the other hand, the standard thermocouples would change in the positive direction over a short period of time due to the positive shift of KP (EP). This change would make the thermocouple shift out of the special range. This can be explained by examining the structural difference between the two before and after insertion to a furnace held at 538°C as shown in Fig. 4.

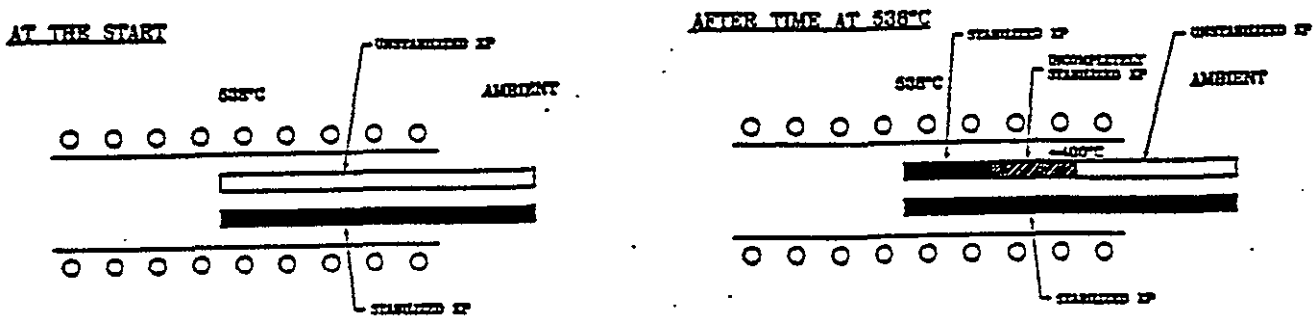


FIGURE 4. COMPARISON OF STABILIZED KP VS UNSTABILIZED KP AFTER EXPOSURE TO 538°C FOR A PERIOD OF TIME

Before inserting into the furnace, the structure of the stabilized KP is short range ordered (shown in black) and is uniform across the entire length. After a certain time at temperature, the structure of this stabilized KP remains short range ordered and is uniform across its entire length as before. In this equilibrium condition, its calibration will have minimal change (within $\pm 1^\circ\text{C}$) upon exposure to the 400 to 600°C range.

However, the situation is different with the standard KP. Before insertion into the furnace, its structure is disordered (shown in white) and is uniform across its entire cross section. Upon exposure to 538°C , the previously standard KP has now three structurally different sections across the temperature gradient from 538°C to ambient. They are: stabilized (short range ordered, shown in black), incompletely stabilized (mixture of short range ordered and disordered, shown as shaded section) and non-stabilized (disordered, shown in white). The change of the structure from uniformly disordered to this three structurally different zones contributes to the positive change of standard KP.

3200 Hour Laboratory Stability Tests At 538°C On Stabilized K and E Thermocouples

A laboratory stability test was conducted as part of the development program for these new products. The temperature was at 538°C in air. The test was conducted using 6.4 mm (.250") and 3.2 mm (.125") diameter stabilized Type K and E metal sheathed thermocouples for a total of 3,200 hours (4.4 months). During the interim, the thermocouples were calibrated at 538°C in situ for 23 times. The test results has demonstrated that the calibration of both the stabilized Type K and stabilized Type E metal sheathed thermocouples is essentially unchanged during the entire period of 3200 hours (7).

Results Of Field Tests At Ontario Hydro

A total of nine 6.4 mm (.250") diameter stabilized Type K and four same diameter stabilized Type E duplex metal sheathed thermocouples were submitted to the utility company for field evaluation. This was initiated during the Spring of 1994 after early encouraging laboratory results. The initial field results on stabilized Type K have been reported in December 1994, Reference (1). This data, plus the additional new results on Stabilized K and all new data on Stabilized E from 1994 to 1996 are included in this paper. Before presenting the field test results, the factors affecting the calibration of samples will first be discussed. These factors are the method of recalibration, the depth of immersion and the effect of cooling rate.

Method Of Recalibration, Depth Of Immersion And Cooling Rate

All the thermocouples, were initially calibrated at the Calibration Laboratory. After installation and use at the Utility Company, they were periodically removed during the shutdown and sent back to the Cal Lab for recalibration. Upon completion, the thermocouples were returned to the Utility Company and reinstalled at their original location inside the turbines for the next start-up operation. It should be noted that the depth of immersion of the thermocouples in the furnaces in both cases was 12 inches. This length is sufficient to obtain an accurate temperature measurement.

The effect of depth of immersion factor is described as follows: The composition and structure of a new thermocouples are uniform across its entire length. Under this condition, the value of the calibration is dependent on the composition of the positive and the negative thermoelements, as well as the difference in temperature between the hot and the cold junction. It is independent of the depth of immersion of the thermocouple or the temperature gradient of the furnace. However, when a change in either composition or structure of the thermoelements occurs, the calibration would also depend on the depth of immersion and furnace temperature gradient. Experience showed that a decrease in depth of immersion (leaving some of the heat affected zone out of the furnace) would increase the magnitude of the calibrated value. On the other hand, an increase in the depth of immersion would decrease the magnitude of the calibrated value. Difference in furnace temperature gradient is believed to have an effect but to less extent.

The reproducibility of calibration of the stabilized Type K and E thermocouples for the 538 °C laboratory tests at the Calibration Laboratory has been shown to be ± 0.3 °C. However, the reproducibility of the stabilized Type K and E thermocouples field tested at the Utility Company and recalibrated periodically at the Calibration Laboratory is ± 0.6 °C. This is attributed to the difference in temperature gradient between the field test at the Utility Company and the Calibration Laboratory furnace even though the depth of immersion of the thermocouples in both cases were the same, 12 inches.

In a laboratory environment, the calibration of stabilized Type K and E metal sheathed thermocouples after air cooling from 538°C to room temperature was essentially unchanged. In power plant operation, the cooling rate of the steam turbines and their thermocouples from 538°C to ambient was much slower than air cooling. Thus, the calibration of these thermocouples were also essentially unchanged.

Total time Of Operation

The total time of operation of the steam turbines is defined as the time the turbines are operating at 538°C plus the time required to reach and to cool down from this operating temperature. At the Utility Company, the average start-up time was 8 hours, which included 2 hours heating up to and 6 hours cooling down from 538°C. The time the turbines were down (not in use) was not included.

Field Test Results On Stabilized Type K And E Thermocouples

During the period from the Spring of 1994 to the Fall of 1996, nine stabilized Type K metal sheathed thermocouples were field tested at 538°C for a total time of operation of up to 4,100 hours (92 start-ups). The test results of Sample No. 1, with 49 start-ups for a total time of 1,400 hours and Sample Nos. 2, 3, 4 and 5, with 92 start-ups for a total time of 4,100 hours, are shown in Fig. 5. The test results of Sample Nos. 6, 7, 8 and 9, with 88 start-ups for a total time of 2,972 hours, are shown in Fig. 6. It was observed that, since the data scatter was within the reproducibility of the test, there was no significant change in the calibration of any of the nine stabilized Type K thermocouples during the entire period of operation up to 4,100 hours at 538°C.

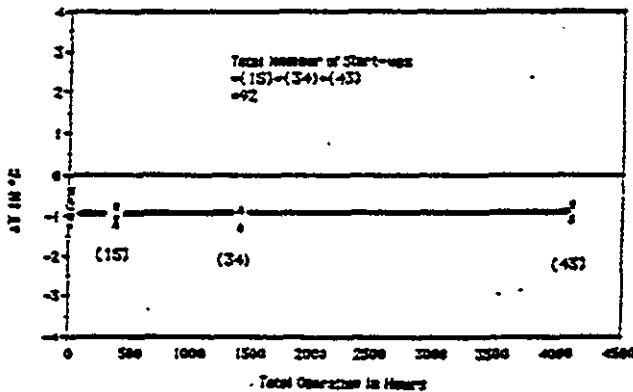


Fig. 5 calibration of 6.4mm (0.250") Stabilized Type K after 4100 hours of Operation at 538°C

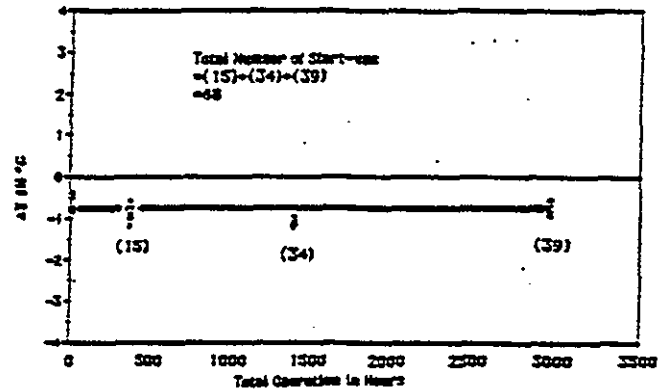


Fig. 6 Calibration of 6.4 mm (0.250") Stabilized Type K after 2972 hours of Operation at 538°C

The four duplex Stabilized Type E metal sheathed thermocouples (equivalent to 8 single thermocouples) were field tested at 538°C for a total time of operation of 5,896 hours (102 start-ups). The test results are shown in Fig.7. Again, there was no significant shift of calibration of any thermocouples during the entire period of operation of almost 6,000 hours at 538°C.

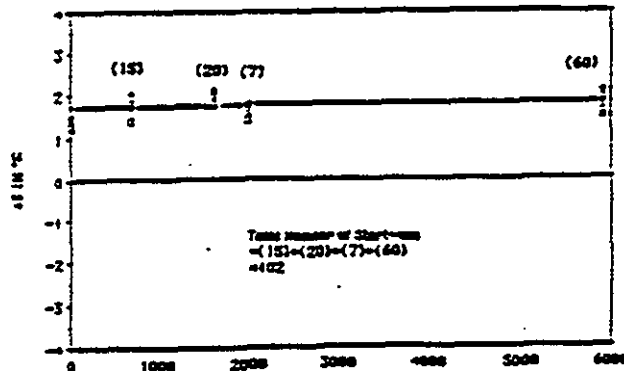


Fig. 7 Calibration of 6.4 mm (0.250") of Stabilized Type E after 5896 Hours of Operation at 538°C

Based on the above field test results gathered at the utility company during the period of 1994 to 1996, both the stabilized Type K and E metal sheathed thermocouples were shown to be stable to $\pm 1^\circ\text{C}$. Thus, we have demonstrated that we have provided a solution to the age old problem of standard Types K and E thermocouples drifting upon exposure to the aging range of 400 to 600°C.

Turbine Efficiency Improvement Via Elimination Of Thermocouple Error

Efficiency calculations based on operating at 2°C lower than the optimum operating temperature of 538°C are as follows:

Assume the average load of generating units is 380 Megawatts (MW) and operates 6,000 hours per year. The increase in fuel cost to operate at lower steam temperatures is shown in Eq. (1) as follows:

$$\$/\text{yr} = \text{ED} \times \text{TC} \times \text{CF} \times \text{CC} \times \text{OPHRS}$$

Where: $\$/\text{yr}$ = increase in fuel cost per year
 ED = efficiency decrease (GE design due to steam temperature decrease in % per °C)
 TC = temperature below optimum (538°C) in °C
 CF = coal flow at average load (Mg/hr)
 CC = coal cost in \$ per Mg
 OPHRS = turbine operating hours (hrs/yr)

For high pressure turbine

$$\$/\text{yr} = 0.0002448/^\circ\text{C} \times 2^\circ\text{C} \times 125.2 \text{ Mg/hr} \times \$55 / \text{Mg} \times 6000 \text{ hrs/yr} = \$20,228/\text{yr}$$

For intermediate turbine

$$\$/\text{yr} = 0.000369/^\circ\text{C} \times 2^\circ\text{C} \times 125.2 \text{ Mg/hr} \times \$55 / \text{Mg} \times 6000 \text{ hrs/yr} = \$30,491/\text{yr}$$

For one unit, one high pressure turbine and one intermediate turbine, the annual savings would be \$50,719

For 4 units, this would amount to over \$200,000 a year

Conversion To Stabilized Type K And E Metal Sheathed Thermocouples Upon Demonstrated Stability At 538°C After Field Tests

Upon completion of the 2 year field tests on stabilized Type K and Type E metal sheathed thermocouples yielding the favorable test results as described in this paper. The above mentioned station of the Utility Company is to be completely converted to the use of the above mentioned thermocouples for the sensing and control of temperature, throughout their entire plant. Unit 3 conversion was completed in 1996 and the rest of the plant is to be completed in 1997.

Impact on the Utility Industry WorldWide

With over 70,000 units in operation by 10,000 utilities worldwide, and assuming that (1) the generating units are half as powerful as Lambton, (2) that half of all utilities use thermocouple sensors and (3) that half of them converted to stabilized Type K or E thermocouples, the annual savings in fuel cost would be \$400,000,000.

$$70,000 \times 1/2 \times 1/2 \times 1/2 \times 50,000 = 400,000,000$$

Summary

- (1) This article documents the results of two year field tests which led to the conversion from standard Type K thermocouples to stabilized metal sheathed Type K and E thermocouples in the latter part of 1996 for sensing and control of steam temperature at 538°C throughout the entire plant of Generating Station of Ontario Hydro, Canada
- (2) Stabilized metal sheathed Types K and E thermocouples were developed and processed by understanding and harnessing the basic aging phenomenon of their common positive thermoelement, a 90 nickel 10 chromium alloy. These thermocouples meet their respective special tolerance initially and remain essentially unchanged upon exposure to the 400 to 600°C range for a long period of time.
- (3) After field test temperature of 538°C, no significant change from initial calibration was observed on any stabilized Type K metal sheathed thermocouple for a total operating time at temperature for 4,000 hours with 90 start-ups, or on stabilized metal sheathed Type E thermocouple for a total operating time at temperature of 6,000 hours with over 100 start-ups.
- (4) The use of stabilized Type K and E metal sheathed thermocouples resulted in the agreement of the operating temperature with the optimum steam temperature of 538°C, or essentially zero efficiency loss. This translates to an annual fuel savings of \$200,000 for this generating station with four 500 megawatts units.
- (5) Annual fuel savings worldwide could reach over \$400,000,000.

Reference

- (1) Wang, T. P., Bediones, D., Henrikson, H.J. and Janhunen, E.J. "Improved Operating Efficiencies Through Used of Stabilized Thermocouples", Proceedings of Power-Gen America Conference Vol D 1-2, p. 289 (1994)
- (2) ASTM Standard Vol. 14.03 on Temperature Measurement E230-93 (1996)
- (3) Sibley, F.S., Spooner, N.P., and Hall, B.F., "Aging in type K Thermocouples" Instrument Technology, Vol. 15 No. 7, p. 53 (1968)
- (4) Wang, T.P., and Wells A., ASME IGTI Second International Symposium on Turbo Machinery, Vol. 1, p 304 (1994)
- (5) Wang, T.P., and Starr, C.D., ASTM Journal of Testing and Evaluation, Vol. 8, p. 192 (1980)
- (6) Starr, C.D., and Wang, T.P., "The Electrical Characteristics of a Nickel-Chromium-Aluminum-Copper Resistance Wire", Proceedings of the Institution of Electrical Engineering, Vol. 50 Part 3, p. 811 (1957)
- (7) Wang, T.P., Bediones, D., and Allen, M.G., "Recent Advances in Temperature Sensors", ISA Advances in Instrumentation and Control, Vol. 50, Part 3, p. 811 (1995)