ADVANCED THERMOMETRICS FOR FOSSIL POWER PLANT
PROCESS IMPROVEMENT

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Advanced Thermometrics for Fossil Power Plant Process Improvement

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ABSTRACT

Improved temperature measurements in fossil power plants can reduce heat rate and uncertainties in power production efficiencies, extend the life of plant components, reduce maintenance costs, and lessen emissions. Conventional instruments for measurement of combustion temperatures, steam temperatures, and structural component temperatures can be improved by better specification, in situ calibration, signal processing, and performance monitoring. Innovative instruments can enhance, augment, or replace conventional instruments. Several critical temperatures can be accessed using new methods that were impossible with conventional instruments. Such instruments include high temperature resistance temperature detectors (RTDs), thermometric phosphors, inductive thermometry, and ultrasonic thermometry.

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I. Importance of Accurate and Reliable Temperature Measurements in Fossil Power Plants

1. Critical Temperatures in Fossil Plants

Temperatures are the primary process variables in a fossil plant that reflect the operation and efficiency of power production and which can be measured to a useable accuracy. These temperatures reflect the input of fuel and air to the combustion process, the composition of gases in the exhaust, and the efficiency and quality of steam production. The temperatures also quantify factors that impact the reliability of plant components and their maintenance and replacement.

In a typical plant steam cycle, temperatures range from about 300°F for preheat, about 650°F for main heat, and up to about 1050°F for superheat, all well within the capabilities of conventional thermocouples and RTDs. Temperatures in the combustion chamber possibly exceed 2000°F, which approaches limits of base metal thermocouples and exceeds the useful range of industrial RTDs, particularly in a high vibration application.

Thermocouples provide accuracies to within a few percent of operating temperatures; RTDs can be accurate to a few tenths of a percent under plant conditions. Thermocouples have a useful life of up to about 18 months at 1000°F but drift as much as 6 °F in a year's time (8800 hrs) at that temperature. RTDs may fail in half the time but drift only about one-tenth as fast. Wide variations in drift and life time of RTDs from the same or different manufacturers have been observed. (Ref. 1). An improvement in drift rate of a factor of ten and a factor of at least three in life time could probably be achieved by better sensor specification, design, manufacture and qualification.

The cost impact of deficient performance of thermometers in fossil electric plants have been estimated both from the increased cost of fuel and the decreased life time of boiler components. A 5°F over estimate of the steam temperature in one unit could cost $200 per day (about the cost of a commercial thermometer) in fuel costs; a 10°F under estimate could reduce life expectancy of boiler tubes by 28% -- a cost for maintenance and replacement much in excess of the fuel cost penalty. In more general terms, a conservative estimate (Lindsey, Duke Power, 1991) of the cost impact of a 1% error in temperature for a one megawatt power plant is $18,000 per year.

Improvements in industrial RTDs should reduce the inaccuracy of the RTDs by a factor of five -- to an uncertainty of about 1°F -- and the drift rate by a factor of ten to about 0.5 °F/year as shown by other drift tests. In addition, suitable accuracy can be maintained by in situ or off line calibration of the RTDs. Thermocouple accuracy better than 10°F at 1000°F or drift rates less than 6°F per year may be difficult to achieve. Calibration of thermocouples in service to achieve accuracy improvements would require their frequent replacement.
2. RTD and Thermocouple Drift and Failure Experience

Drift rate of RTDs has been studied in a half dozen or so programs within the last decade. The results indicate that under most favorable laboratory conditions with the best available commercial RTDs the drift rate at 1000°F is about 0.03°F per month, in plant conditions it is at least 0.1°F/month and may be as large as 2°F/month [1]. Drift rates for RTDs and thermocouples at various temperatures are given in Figure 1.

![THERMOMETER DRIFT AT VARIOUS TEMPERATURES](image)

Figure 1. Drift Rates of RTDs and Thermocouples

These data include results from Analysis and Measurements Services (AMS) [Ref. 2], EPRI report TR-103043 [Ref. 3] AND TR-103099 [Ref. 4], ORNL internal reports, previous reports by PG&E [Ref. 5], reports by Rosemount Electric Corp. The data are displayed as the percentage drift rate of the absolute temperature in kelvins per thousand hours of testing (%T(K)/1000 hr) plotted against the reciprocal of the absolute temperature. This plot is referred to as an Arrhenius plot used to determine activation energies in chemistry, and provides a basis for relating tests conducted at different temperatures for various lengths of time.
time on different sensors. (A drift rate of 0.01 %/khr is equivalent to a 0.1 °F/month.) These data show the lower drift rates for RTDs than thermocouples at various temperatures. The Arrhenius plot may be used (with caution) to extrapolate test results at lower temperatures to higher temperatures assuming the drift process does not change but merely increases in rate. It is unlikely that commercial RTDs will drift less than the interpolated line, but can drift faster by at least a factor of 100 (two decades). Scatter in the data is due to the variation in quality of test specimens and, to some extent, the way in which drift data were taken and reduced to rates.

The data reported in PG&E 96 report [Ref. 1] indicate drift rates of from 0.1 to 2.0°F/month. These drift rates when converted to the Arrhenius rate (%T in kelvins per 1000 hr of exposure) and plotted on Figure 1 (labelled as PG&E 96) at 1000°F appear to be higher than RTD drift rates obtained from other studies, probably because of the added impact of plant vibration, and to be higher than the best thermocouple drift rates, but not unreasonably high. When the data are considered in units of °F per month, the drift in RTDs in fossil plants in an 18-month period range from about 2° to 36 °F or 0.2 to 3.6%F at 1000°F. In order to maintain even a one-half percent accuracy, the RTDs might need recalibration or replacement more often than every two years, assuming that they had not failed sooner.

The results of the PG&E 96 report show a wide range of drift rates (from 0.1 to 2°F per month) and failure rates (from 2 to 19 months to failure) at 1000°F. The data for test results on individual RTDs show large variations in drift rate of each sensor from test to test conducted at two-month intervals. It is difficult to select a particular drift rate from the test results shown for most of the sensors. Those results on RTDs from two or three suppliers are consistent enough to indicate drift rates of from 0.1 to 0.3 °F/month. It would be very difficult to predict the drift rate of an RTD obtained from any of these suppliers within a factor of about twenty. It is likely that the inconsistencies in the observed data are due to the adverse impact of the handling and testing of the sensors. Sensor handling during removal, off-line calibration, and reinstallation in the plant may have contributed significantly to the rates of drift and failure reported. The need for in situ calibration to track and correct for drift is indicated by this interpretation of the results.

If the information on accuracy and drift rates for RTDs at 1000°F are extrapolated to combustion chamber temperatures of up to 2000°F, drift rates of at least three times greater and inaccuracies of several percent would be expected using conventional sensor materials and methods. Other technology could be employed to obtain and maintain an accuracy of 1% of reading.

The failure rates in the PG&E 96 report all seem to be shorter than would be expected, even with some variations in RTD characteristics from different manufacturer. Reports of experience in observing failure rates are few, the current draft report by PG&E [Ref. 1] being the most recent. In testing of four RTDs from each of six manufacturers and four thermocouples from each of two manufacturers, failures due to open circuit or off scale resistance readings occurred at from 2 to 19 months, with a mean of 9.3 months. Thermocouples failed at from 4 to 19 months with a mean of 15.6 months. The thermometers were installed in several different plants and operated at temperatures of 1000-1050°F. Failure of the RTDs reported by Fromberg may have been due to (a) operating RTDs above temperatures for which their
performance was demonstrated, (b) excessive vibration in the plant application, or (c) handling of the RTDs during removal, off line calibration, and reinstallation in the plant. The latter (c) possibility could be avoided by in situ calibration of the RTDs.

II. Improvements in the Use of Conventional Temperature Sensors

1. Specification and Procurement

Specifications require that the article being obtained is suitable for the purpose that the buyer intends it to be used for. "Specifications" provided by a vendor in catalog literature seldom address the particular conditions of use that the article is being procured. Consensus specifications for RTDs include the German DIN standard, the Japanese 1604, and the U.S. ASTM E 1135, each of which is suitable for general industrial use, but not necessarily for highly reliable utility applications. For these applications, additional manufacturing and acceptance testing is needed to assure that these articles are qualified for use. Such testing and specifications add to the price of the article but may reduce operational and replacement costs.

2. Drift and Failure Reduction

The initial drift in service could be significantly reduced if the RTDs were preconditioned by exposure to the operating temperatures for several months before calibration and installation: 6-12 months at 1000°F or probably less if exposed to higher conditioning temperatures. Care in fabrication of the thermometers to eliminate impurities and moisture in the sheathed sensors, better choices of materials, and better structural design could reduce failure rates. Many failures occur at the cold end termination which could be prevented by better support of the leads. Other failures may be due to the impact of fairly high vibration levels at the higher operating temperatures in fossil plants. As a general strategy, thermometers designed for 1200°F service would perform better at 1000°F than those generally available.

3. In Situ Calibration

Sheathed RTDs installed in thermowells in the steam lines in fossil plants can be removed periodically, recalibrated, replaced, and the appropriate corrections made in the signal processors and temperature displays. Some RTDs operated at high temperatures have not been removed without breaking them. [Thermocouples cannot be removed and recalibrated off-line; they must be replaced if they are thought to have drifted.]

Johnson noise thermometers do not drift. Their present development provides several methods of in situ calibration of conventional RTDs installed in the fossil plants. Noise temperatures and dc resistance temperatures can be obtained concurrently on the same sensor, allowing either periodic calibration upgrade during plant operation at the operating temperature, or continuous simultaneous calibration upgrading of each thermometer. [Johnson noise calibration of thermocouples is not feasible with conventional thermocouple designs.]

ORNL, University of Tennessee, and EPRI have developed several Johnson noise signal processors that can be used in harsh industrial environments. They correct for, or eliminate,
problems of signal attenuation in long signal cables, microphonic noise induced by vibration of the sensors, EMI, and differences in ground potentials in the plant. Two systems are being evaluated: (1) a tuned circuit input to the noise amplifier that produces a voltage across a capacitor that is directly proportional to the sensor’s temperature and is analog processed, shown in the Figure 2, and (2) a voltage correlation system that reduces the contribution of noise by the amplifiers and the signal cables and is digitally processed, shown in Figure 3.

DC RESISTANCE & JOHNSON NOISE SYSTEM FOR IN SITU CALIBRATION OF POWER PLANT RTDs

DUAL-MODE ANALOG NOISE SIGNAL PROCESSOR

![Diagram of analog tuned circuit Johnson noise signal processor](image)

Figure 2. Analog Tuned Circuit Johnson Noise Signal Processor

The digital processing of the second system provides means for detecting and rejecting spurious noise and for verifying the noise temperature by comparing measurements in different frequency bands.
Figure 3. Digital Correlated Voltage Johnson Noise Signal Processor

Further developments in progress are expected to reduce uncertainties to about 0.2% by eliminating spurious noise due to EMI, ground potentials, and vibration.

4. Signal Processing and Channel Alignment

Digital signal processors for RTDs and thermocouples installed in fossil power plants could reduce the whole-channel uncertainties in temperatures by accommodating individual sensor calibration differences and upgrading the display following recalibration. In some cases, if analog conversion uses a linear approximation of the resistance-temperature relationship at the operating point and an incorrect calibration table is used, such as using a JIS 1604 instead of an ASTM E1137, errors at 1000°F could be as large as 30°F.

III. Advanced Temperature Measurement Methods

1. High Temperature Resistance and Johnson Noise Thermometers

RTDs have been available from several manufacturers that will provide accurate and reliable service up to about 1200°F (650°C). A dozen or so dual-element 100-Ω RTDs purchased from Rosemount about 15 years ago operated successfully in the Fast Flux Test Facility reactor inHanford Washington at temperatures up to 650°C for more than 10 years with only one reported failure and changed in calibration by only 1%. This performance was due in part to an intensive qualification program developed by ORNL. Other RTDs have been
advertised for service up to 1560°F (850°C), but we have no information on their stability or reliability. Recently, several manufacturers have described development of RTDs for temperatures greater than 1800°F (1000°C). ORNL developed RTDs suitable for temperatures to 1100°C (2000°F) for a space nuclear application (the SP100 program) that used materials compatible with molten lithium. One objective of the current EPRI program is the adaptation of this technology to the combustion environment in a fossil plant.

High temperature RTDs (HTRTDs) should provide the ability to measure flame temperatures and the fireball location in the fossil plants. Some measurements of the flame temperatures have been made recently at TVA’s Kingston Steam Plant using Inconel sheathed Type K thermocouples, which indicated temperatures up to about 1050°C. No damage to the sensors occurred in the brief 20-day test. These temperatures could be measured more accurately with HTRTDs and provide better ability to locate and control the fireball, leading to less flame damage to the boiler tubes lining the combustion chamber. Their calibrations can be confirmed in situ using Johnson noise.

2. Thermometric Phosphors

Phosphors have been used over the past decade to measure temperatures in gas centrifuges and other immersion or noncontact applications. Their use can extend to temperatures as high as about 1500°C and they’re exceptionally stable. Their application to fossil power plants—includes the steam and combustion chamber measurements and probably other determinations of temperatures of hot surfaces.

The physical property underlying phosphor thermometry is the monotonic optical decay time decrease of a wide variety of phosphor materials with increasing temperature. Phosphors absorb short wavelength light and re-emit some of the light at a longer wavelength characteristic of the phosphor. The light emission process competes with non-radiative (phonon mediated) decay modes. The phonon process probability increases with temperature—providing the temperature dependence of the fluorescence process.

Phosphor thermometry has several inherent, advantageous features: first it is electromagnetically immune, second it does not rely on knowledge of emissivity, third it is only subject to drift as phosphor short range lattice order is altered, and finally it is virtually insensitive to cabling and connection effects.

Phosphor thermometry is suitable for deployment throughout power plants. Phosphor based thermometry probes can be fabricated for deployment directly in combustion environments. The only apparent mechanical or thermal constraint to the technique is the durability of protective casings available. Phosphors have been demonstrated from cryogenic temperatures to ~1500°C (little effort has been invested in extending the upper range).[6] In addition to deployment in a probe configuration, phosphors can be adhered to surfaces (which remain clean) and addressed across free space. This is particularly useful in rotating applications such as turbine blades.[6]
Figure 4. Thermometric Phosphor Probe and System

The precision which temperature may be determined in phosphor thermometry varies both with the phosphor compound selected and the signal processing electronics and technique. Each phosphor compound has a temperature range over which radiative and non-radiative decay modes compete, and the amount the phosphor decay constant varies with temperature depends on the particular compound used. A typical phosphor is Y$_2$O$_3$:Eu that has a fluorescence lifetime variance from 1.4 ms at 400°C to 0.5 µs at 1000°C. Measurement precisions of roughly 10 mK have been reported using similar materials by several groups.[6, 7, 8] Since the fluorescence process only drifts as the short range lattice order of the phosphor is altered, virtually no drift is anticipated in the fluorescence decay time. However, overall long-term measurement system drifts are expected to be on the order of 0.5°C.[9] The absolute accuracy achievable through phosphor thermometry has not received a thorough treatment. Although in many phosphors the actual fluorescence decay time variation with temperature is exponential to the limit of available measurements, several phenomena combine to limit the absolute measurement accuracy achievable. The fluorescence signal strength often varies by more than three orders of magnitude with temperature—making detector gain linearity a critical parameter. In addition at high temperatures the environmental blackbody radiation adds a strong background component to the signal. Moreover, the excitation signal strength is much stronger than the phosphor signal and its reflection can cause distortion in the fluorescence measurement. Performing an accurate exponential fit to the decay pulse is also limited by the available digital sampling bandwidth. Overall, using standardly available components, an absolute accuracy of measurement of roughly ±2 K is readily achievable with Y$_2$O$_3$:Eu at 1000°C (or 4°F at 1800°F). No fundamental phenomenon, however, apparently limits the achievable accuracy of measurement from approaching the precision.

3. Ultrasonic, Inductive, or other Thermometers

Ultrasonic and inductive thermometers have been investigated for use in special applications. Ultrasonic thermometers have been used in applications to over 3500°F and offer a wide selection of usable materials for fabrication of delay line sensors. They must be mounted vertically to minimize mechanical interactions between the sensing line and its surrounding structure. Their temperature sensitivity increases with temperature reaching about 1°C at 2000°C, but increased attenuation of the acoustic waves makes their accuracy decrease at the higher temperatures. The ultrasonic sensor may be fabricated as a multipoint device which
allows temperature profiling with a single sensor. The principle of operation may also provide integrated temperature of fluid in pipes or vessels and may be combined with additional sensors to give flow rate or level measurements. [Ref. 10]. Accuracy of ultrasonic thermometers is less than that of RTDs.

Inductive thermometers offer some advantages in noncontact temperature measurement of metal surfaces, possibly to monitor inner surface temperatures in combustion chambers independent of slag build up. Neither of these thermometers provide accuracies comparable to those of RTDs or any significant reduction in drift rate.

CONCLUSIONS

A factor of ten improvement in accuracy of temperature measurements in fossil plants would provide increased revenue and reduced maintenance costs. This improvement can be achieved with an extension of known technology and its application to the power plant environment. Practices involving the specification, procurement, installation, and operation of conventional thermometers could provide improved thermometrics within a year with only minor extensions of existing technology. Major improvements and cost reductions could be achieved within two to three years by their application to fossil plants of demonstrated thermometric methods whose characteristics have been already identified. Advanced developmental RTDs could provide major cost reductions, maintenance reduction, reliability improvements, and energy production increases within the next 5-10 years.

RTDs can now provide better accuracy (better than 0.5%) than thermocouples (1-2%) at temperatures up to 1000°F and can be developed to provide the same improvement at 2000°F with better than 1% accuracy. Drift in RTDs can be reduced to a consistent level of less than 0.4% uncertainty using on-line calibration methods. To maintain a calibration accuracy of less than 1% (10°F at 1000°F), RTDs should be calibrated in situ about every 6-8 months.

Johnson noise thermometers (JNTs) and pulse echo ultrasonic thermometers (USTs) have been developed for other applications and could replace or augment conventional thermometry in fossil plants. The JNT can provide absolute accuracy approaching 0.1% at temperatures up to 1000°F and possibly to 2000°F. JNTs can be used in conjunction with commercial RTDs already installed in fossil plant steam lines to correct for any RTD drift and in combustion chambers to provide long-term accurate measurements of the fire ball temperature and location. USTs can be used for combustion chamber thermometry to temperatures greater than 2000°F in high EMI environments with lesser accuracy.

Fiberoptic sensors that use decay time measurements with thermometric phosphors offer future possibilities for measuring steam line and combustion chamber temperatures in fossil plants to a very small uncertainty (about 0.5% at 2000°F), free from drift. They are immune to EMI and vibration interferences. Costs of individual sensors are small and many individual sensors can be multiplexed to provide redundancy or broader coverage. Industrial grade signal processors and sensor protection need to be developed. Other factors include: range of application, accuracy, signal level, calibration, signal validation, drift rate, response time, insulator shunting at high temperatures, EMI and vibration interferences, signal processing,
process interface (protection tubes), cable requirements, signal interface and display, durability, replacement, deployment, availability, and initial cost.

REFERENCES:


L. J. Dowell, Investigation and Development of Phosphor Thermometry, PhD Dissertation, the University of Virginia, 1989.
