Final Report

Remote Temperature Measurement in Hostile Industrial Environments with Microwave Radiometry

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Executive Summary

This project investigated the feasibility of developing a remote temperature measurement instrument for energy-intensive industries. Existing remote temperature measurement techniques based on infrared radiation fail when excessive amounts of dust, smoke, or other particulates are present. We found that a remote temperature measurement instrument using microwaves demonstrated performance superior to infrared instrumentation in laboratory and field trials when dust or steam was present. Since improved temperature measurement helps improve energy efficiency and quality in a wide variety of industrial processes, making the new microwave instrument commercially available should lead to reduced energy usage, improved quality, and better competitiveness in a number of energy-intensive industries such as food processing and cement manufacturing. These improvements can lead to lower-priced products of improved quality for the consumer, and can contribute to the nation's energy independence.

Project Description

1. Original project goals and objectives

Here are the project goals and objectives as stated in the original proposal for this project:

> Project goals and scope. The two primary goals of this project are (1) to build a microwave radiometric temperature sensor suitable for field use at industrial sites and (2) to test the sensor at a variety of representative industrial sites to verify its usefulness under conditions that prevent other remote temperature sensors from operating. Other goals include the publication of results as appropriate and the eventual transfer of technology to a firm interested in commercializing the product.
>
> Statement of goals and objectives. The overall objective of the project is to demonstrate the usefulness of microwave radiometry in remote temperature measurement situations in industry where other temperature-sensing technologies cannot be successfully used.

2. Variance from original goals and objectives

The first goal of constructing a microwave remote temperature measurement instrument suitable for field use was achieved successfully. A series of redesigns of the original instrument produced a unit that was suitable for field trials beginning in April of 2004. Since that time, the instrument has been used in a total of four field trials: one at a metal foundry and three at a cement plant.

The second major goal was to test the sensor at a variety of industrial sites in order to show it works under conditions that prevent other types of remote temperature sensors from operating. The field trial at the metal foundry was inconclusive, but the three field trials at the cement plant showed that the instrument developed during this project should be useful for monitoring temperatures inside a rotary cement kiln which cannot be monitored with current instrumentation. In addition to the field trials, numerous laboratory tests show the superiority of the instrument to conventional remote temperature measurement approaches. One of these tests involved the measurement of a food product.

Other goals included the production of intellectual property. Since the project commenced, four conference papers describing the instrument and its uses have been presented at technical conferences [1,2,3,4]. One additional paper is being revised for publication [5]. In July of 2004, a patent application on certain aspects of the technology was filed [6]. With regard to an industrial partner for eventual commercial production, in the fall of 2004 a Phase I Department of Energy STTR grant for further research and development activities was awarded to a team consisting of ProSensing, Inc., the PI (Stephan) and co-investigator (J. A. Pearce).

The only significant variance between the original goals and objectives and the achieved goals and objectives concerns the variety of industries used for field test sites. We originally anticipated testing the instrument at three different sites representing three different industries. Delays in developing a truly field-usable instrument did not leave enough time in the project to perform field tests at three different sites. However, we feel that enough on-site experience and data were gained from the three field tests at one site (the cement plant) to justify the omission of a third industrial field-test site.

3. Discussion of Work Performed, Findings, Results, and Analysis

This section is organized by task/milestone descriptions as presented in the original project proposal, which are given in *italics*.

Task 1.1 *<u>Radiometer Design</u>. The radiometer unit will be designed to be compact, stable, reliable, rugged, and portable enough for extensive field tests. The PI will lead this design effort and UT staff will assist.*

There were significant technical challenges involved in developing a microwave instrument for remote temperature measurement that was (1) sensitive and stable enough to produce usable data and (2) compact, rugged, and inexpensive enough to be used in hostile industrial environments. Most earlier designs of this type have been for scientific or military purposes where low cost was not the primary objectve. Two critical decisions were made early in the design process: (1) to use a commercially available satellite-TV receiver module to perform most of the microwave processing, and (2) to enclose the entire unit (except for a control cable and data recorder) in a rugged NEMA-rated steel housing of a convenient size (approximately 1 cu. ft.). These choices produced a low-cost unit that has been rugged and portable enough for use in the hostile environment of a cement plant.

Adapting the commercial microwave receiver for use in a radiometer involved the development of external microwave circuitry and low-frequency analog and digital electronics. Problems with stability and power-supply circuits delayed the completion of the design beyond the originally scheduled date of 1st qtr. 2003 to the 2nd qtr. 2004. These problems were resolved with an extensive redesign of the low-frequency electronics. Since the installation of this redesigned circuit, the instrument has proved to be sufficiently reliable and stable for numerous field trials.

Task 1.2 *Equipment and Component Procurement. Certain test equipment for field testing and servicing is required at SWT, and components for the radiometer unit will be purchased at this time.*

In addition to parts and supplies needed for the construction of the instrument, under a cost-sharing agreement with Texas State University an Agilent E4405B spectrum analyzer (approx. cost $24,000) was purchased for this project. This equipment has proved essential to tests and evaluation of the instrument and related issues.

Task 1.3 *Radiometer Assembly. The radiometer will be assembled at UT under the supervision of the PI and co-investigator. Initial troubleshooting and modifications as necessary will be performed at this time.*

As explained under Task 1.1 above, assembly and troubleshooting took longer than anticipated. Extensive redesigns produced a reliable and usable instrument.

Task 2.1 *Lab Verification Tests. These tests performed at UT will verify the accuracy and stability of the unit with laboratory-grade equipment.*

Important characteristics of the temperature measurement instrument include accuracy, linearity, stability, and noise performance. Special LabView software was written for the purpose of calibrating and evaluating these performance characteristics, and was used extensively in the development process. In addition, for temperature calibration purposes a heated calibration microwave load was constructed (see Fig. 1, Supplemental Information).

Since the effective microwave temperature of the heated calibration load can be estimated with an accuracy of approximately ±2 C, it served as the primary calibration standard for all radiometer tests. A secondary standard consisting of a noise-generating microwave diode and a calibrated microwave attenuator provided a continuously adjustable microwave temperature source whose effective temperature could be varied from room temperature up to approximately 6000 K (5727 C). The instrument's linearity was measured with reference to the secondary standard using calibration software. A typical result from this measurement is shown in Figs. 2 and 3 (Supplemental Information), taken from data obtained in March of 2005.

Calibration is complicated by the fact that the two different primary fields of application will require two different temperature measurement ranges. The interior temperature of cement kilns can be in excess of 1300 C, while accuracy requirements in this application in terms of ±C error are modest (on the order of ± 25 C). This high input temperature range is in contrast to the relatively low range of input temperatures required for food processing applications. Most food processing takes place at temperatures below about 260 C, but accuracy requirements are tighter (on the order of ±5 C). If the temperature of boiling water (100 C) is taken as the upper limit for food processing, a measurement range of 20 C to 130 C is adequate.

For this reason, the instrument was designed to operate in one of two range modes. In the high-range mode, the maximum output voltage of 10 V corresponds to an input temperature of approximately 1400 C. In the low-range mode, the maximum output voltage occurs when the input temperature is about 130 C. The instrument's mode can be changed from low range to high range by simply changing one connectorized microwave component and making one potentiometer adjustment. The data in Figs. 2 and 3 show data taken with the instrument in the high-range mode.

As Fig. 2 shows, from room temperature to approximately 850 C, instrument linearity is within ±5 C, and is still within ±18 C over the entire input temperature range. Changing modes from high range to low range leaves the relative linearity unaffected, but since the range is reduced by about a factor of 10, the linearity in terms of absolute error in degrees C improves to approximately ±0.5 C over most of the range.

The absolute accuracy of the instrument depends at present on the accuracy of the primary and secondary calibration standards. The primary standard was calibrated with thermocouples checked against standard mercury-glass thermometers. Although a detailed accuracy analysis has not been performed, we estimate the probable absolute error of a given low-range measurement is on the order of ±4 C, and proportionally greater for the high range.

The "noisiness" (standard deviation of a large number of measurements of a constant temperature) of a microwave temperature measuring instrument of this type is limited by fundamental physical considerations. This instrument performs within a factor of about four of the theoretically ideal minimum of noise. When the instrument is used on the low range (maximum input temperature of about 130 C), the equivalent standard deviation of temperature measurements is approximately 1.3 C with an integration time constant of 10 ms. If longer integration time constants can be used (which means fewer samples per unit time), the standard deviation can be reduced to less than 0.1 C, which is much smaller than the probable accuracy of the measurement.

All these tests were performed with the instrument in a controlled-temperature laboratory environment. We did not have the facilities to measure the instrument's accuracy as its environmental temperature varied. Indications are that as long as environmental temperature changes are relatively slow, the instrument's internal temperature compensation system should operate well to make its output almost independent of environmental temperature.

Besides calibration tests, numerous laboratory tests were performed to demonstrate that the instrument performs better than an infrared remote temperature sensor under conditions involving airborne particulates in the sensing path. In one test, the instrument was pointed at a carbon-bearing target heated by a hotplate. Both the microwave and an infrared remote temperature sensor recorded data as dense water fog from submerged dry ice was introduced into the path between the material and the sensors, as shown in Fig. 4 (Supplemental Information). While the fog caused severe scattering of the IR signal which produced an error in the IR reading of about -20 C, the microwave instrument temperature reading was virtually unaffected, as Fig. 5 (Supplemental Information) shows.

In a related laboratory test, a dense cloud of dry powdered lime ($CaCO_3$) was introduced between a heated carbon-bearing object and both microwave and IR temperature sensors, and similar results were obtained.

Task 2.2 *Field Verification Tests. These tests will be performed at a variety of field sites where materials of known properties and temperatures are being processed. The results of these tests will reveal any problems that may arise in the field before actual field trials begin.*

Two of the field trials may be considered as field verification tests. The first test was carried out on June 2, 2004 on the Texas State University-San Marcos campus in a foundry laboratory where a 125-KW induction furnace was available. Tests were performed on both a piece of heated steel and a carbon (graphite) foundry crucible. As theory predicted, no usable temperature reading could be obtained from the steel sample. However, the interior of the heated carbon crucible produced a strong reading, which indicates that our instrument may be useful in certain special situations in foundry work. During this field trial, the instrument malfunctioned and was repaired over a period of several weeks. It also underwent a redesign and was repackaged in a single housing.

The second field trial/verification test was performed on Sept. 3, 2004 at the Texas-Lehigh cement plant in Buda, Texas. While some useful qualitative data was obtained, this test revealed numerous shortcomings in the way the instrument was mounted and oriented with respect to the target, as well as the need to redesign certain details of the antenna. Changes implemented as a result of this initial field test resulted in improved performance during the subsequent field trials.

Tasks 3.1-3.3 *<u>Field Trials.</u> Three different field sites with high potential to gain advantages from the use of this technology will be identified with the assistance of the industrial partner. At each site, the instrument will be set up in a temporary installation and its output made available to plant personnel for process monitoring and control purposes. After a suitable time (2-4 weeks), comparison of instrument data with other process data and interviews with plant personnel will form the basis of the field trial evaluation.*

A total of four field trials were performed with this instrument during the (extended) term of the project. Two of these trials have been described above. The remaining two field trials both took place at the Texas-Lehigh cement plant.

After improvements in the antenna and instrument mounting were made, a field trial was performed on Nov. 24, 2004. The purpose of this field trial was to establish the proper instrument location for optimum sensing of temperature inside the cement kiln.

While kiln configurations vary, the kiln at the Texas-Lehigh plant is typical of the smaller installations. Fig. 6 (Supplemental Information) shows a cross-section of the hot end of the kiln, which is about 58 meters long and 3.6 meters in inside diameter. The steel kiln lined with alumina firebrick rotates at about 4 RPM. The raw ingredients to make cement enter the kiln at about 1100 C (2000 F), and is heated to a maximum temperature of about 1480 C (2700 F) before exiting into an enclosure called the firehood and traveling to a cooler (not shown) below the firehood. The hottest part of the kiln, called the "burn zone" is between 12 and 15 meters from the fired end. A burner using either coal dust or natural gas provides the heat energy required for the process. The temperature of most interest to the kiln operator occurs on the inner surface of the kiln in the burn zone.

Direct contact with the kiln material for temperature monitoring is generally not possible during routine kiln operation. Although thermocouples can be placed within the kiln and monitored through slip rings or other means, the abrasive and corrosive feedstock quickly erodes or coats temperature probes, rendering them useless. The only standard provision for temperature monitoring is one or more small viewports in the firehood at the hot end of the kiln. In kilns where airborne dust is not a problem, infrared sensors or imaging cameras can provide a good estimate of burn-zone temperature. This method of temperature monitoring has been attempted with the kiln in question, but proved to be unsuccessful because of the high concentration of dust in the kiln.

After studying the kiln setup, we decided to use an antenna for the microwave temperature measuring instrument which efficiently receives radiation from a small zone about ten feet (3 meters) in front of the antenna. In the Nov. 24, 2004 field trial, we positioned this antenna at a variety of locations in front of the kiln viewport. At each location, a straight line from the antenna through the viewport intersected a different point in the kiln. We found that the highest temperature readings measured during this trial correlated reasonably well with the hottest locations in the kiln. Therefore, the instrument was "seeing" through the dust cloud (which is at a fairly uniform temperature) and was measuring temperatures of the kiln interior.

On Mar. 15, 2005, we returned to the cement plant for a fourth field test. We installed the microwave instrument at the location which was previously determined to be optimum for sensing temperature in the burn zone. We operated the instrument continuously during an eight-hour shift and performed an external calibration check once per hour. The instrument provided usable data for all but the last twenty minutes of the run. While details of the data collected during this run are awaiting publication and have been withheld from this publicly accessible report, they indicate that the microwave temperature sensor will be a very useful means of monitoring and controlling cement kiln temperature in situations where infrared sensors cannot operate.

Tasks 4.1-4.2 *Reports. Semi-annual reports will be submitted to DOE on 2/1/2003, 9/1/2003, and 2/1/2004, with a final report no later than 12/1/2004.*

All required reports have been prepared and submitted on schedule.

Conclusions and Recommendations for Further Work

Over the term of this project, we have developed a reliable, stable, accurate temperature sensor which uses naturally occurring microwave radiation to measure temperature through clouds of dust, steam, or smoke. In laboratory tests, we have demonstrated its superiority to infrared temperature sensors in a variety of situations, including the measurement of foodstuffs on a moving conveyor system. Field trials at a metal foundry and at a cement plant show that the instrument can measure temperatures of interest to these industries. An eight-hour test run at a cement plant produced data that can be used for significant control-system improvements and cost savings in cement plants.

The further work that can be done falls into two categories: (1) instrument development and (2) market development.

1. *Instrument development*. The current prototype instrument requires too much hand assembly for marketing at the target instrument cost of $2000 to $4000. Ideally, a complete redesign would lead to a custom-manufactured microwave subsystem integrated with low-frequency electronics in a smaller package that consumes less than the approximately 12 W of power needed by the current prototype. This redesign would result in an instrument which could be marketed for the price range that will make it truly competitive with existing remote temperature sensing technology. Besides the redesign, a number of issues need to be addressed with regard to the optimum antennas for various applications, calibration methods, and other technical questions regarding stability and temperature compensation.

2. *Market development*. More work needs to be done on field tests at a variety of representative industries besides cement manufacturing. Experience has shown that several field trials at an unfamiliar facility are needed before meaningful data can be obtained, because of the need to learn details of the plant setup, process, material characteristics, etc. In the last period of this project, we established numerous contacts in the food equipment industry, including one at a steam pasteurization facility in San Antonio. Further work can include more field trials at this and other food-processing facilities near our laboratories, which are readily accessible without extensive travel.

References

[1] “Prospects for Industrial Remote Temperature Sensing Using Microwave Radiometry,” by K. D. Stephan, J. A. Pearce, Lingyun Wang, and Eric Ryza, *Proc. of the 2004 IEEE MTT-S International Microwave Symposium*, session WE4B-1, pp. 651-654, Fort Worth, Texas, June 6-12, 2004.

[2] “Continuous Non-Contact Remote Temperature Sensing During Microwave Heating With Microwave Radiometry,” by K. D. Stephan and J. A. Pearce, *International Microwave Power Institute Proceedings of the 38th Annual Microwave Heating Symposium*, pp. 38-41, Toronto, Canada, July 14-16, 2004.

[3] “Temperature Measurements Through Dust or Steam for Energy-Intensive Industries,” by K. D. Stephan, J. A. Pearce, L. Wang, and E. Ryza, *IETC 2005 Industry Energy Technology Conference*, paper 17.pdf (CD-ROM proceedings only, 5 pages), New Orleans, La., May 11-12, 2005.

[4] “Cement Kiln Temperature Measurements Using Microwave Radiometry,” by K. D. Stephan, J. A. Pearce, L. Wang, and E. Ryza, *2005 IEEE MTT-S*

International Microwave Symposium, paper TU3A-6 (CD-ROM proceedings only, 4 pages), Long Beach, Cal., June 13-17, 2005.

[5] "Microwave Radiometry for Non-Contact Temperature Measurements During Microwave Heating," by K. D. Stephan and J. A. Pearce, to appear in *Journal of Microwave Power and Electromagnetic Energy.*

[6] "Remote temperature measuring system for hostile industrial environments using microwave radiometry," U. S. patent application no. 20050053118.

Supplemental Information

Fig. 1. Heated calibration load constructed for use with temperature measurement instrument. The microwave load is enclosed in heating tape inside the gray box. Control and power wires lead to the controller installed in the black box, which is also used as a carrying case. In operation, the microwave load temperature is controlled proportionally to within ±1 C of a desired setting.

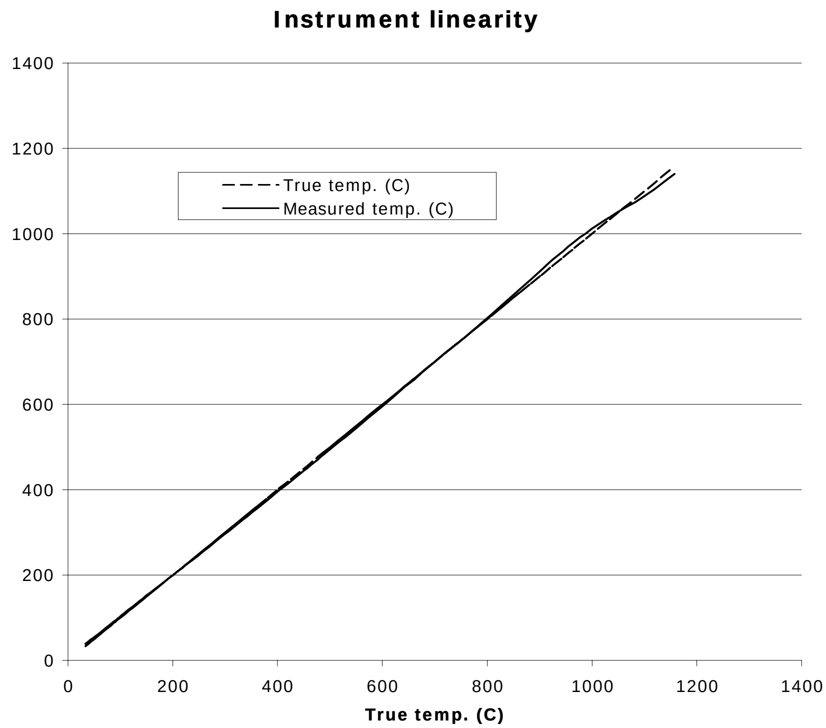

Fig. 2. Measured temperature (C) (solid line) as derived from instrument output voltage vs. actual temperature (C) (dashed line) produced by secondary temperature standard. Dashed line represents perfect linearity relative to secondary standard.

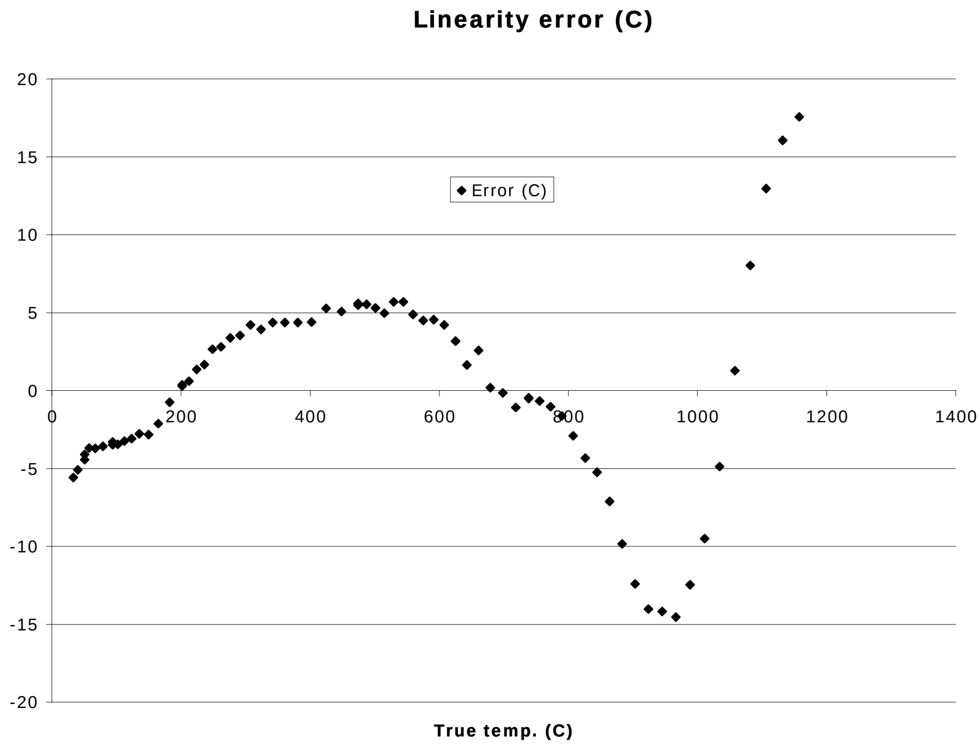

Fig. 3. Linearity error (C) vs. actual temperature (C), calculated as (measured temp. - true temp.) from data in Fig. 2.

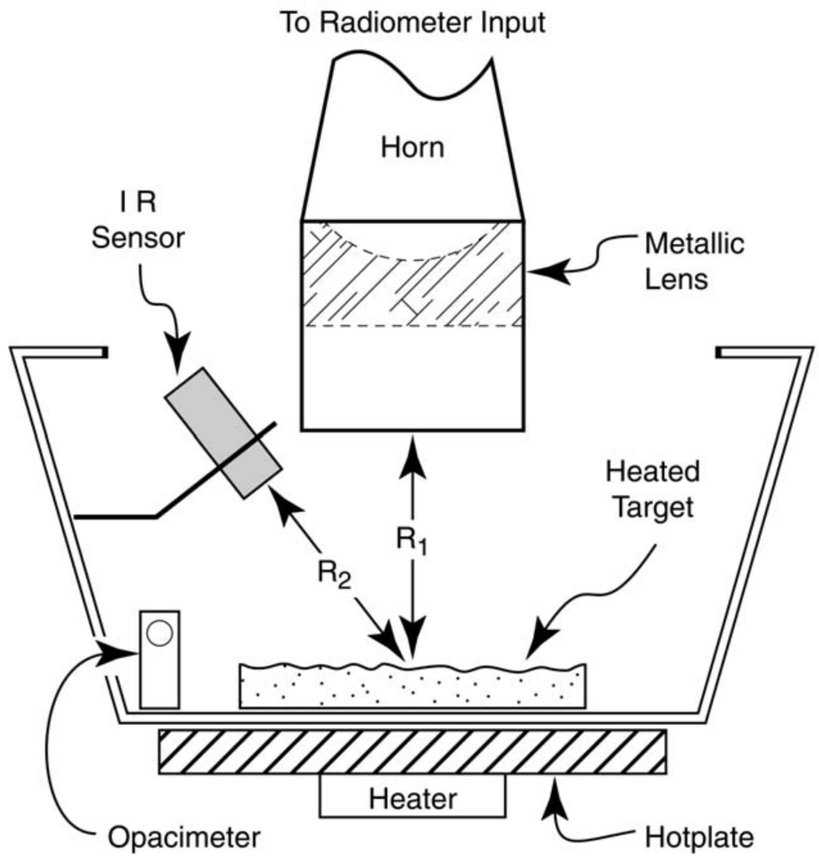

Fig. 4. Laboratory test demonstrating superiority of microwave temperature sensor (radiometer) over IR sensor using water fog. Distance R_1 = 12. 7 cm, R_2 = 13. 5 cm. (from Ref. [1])

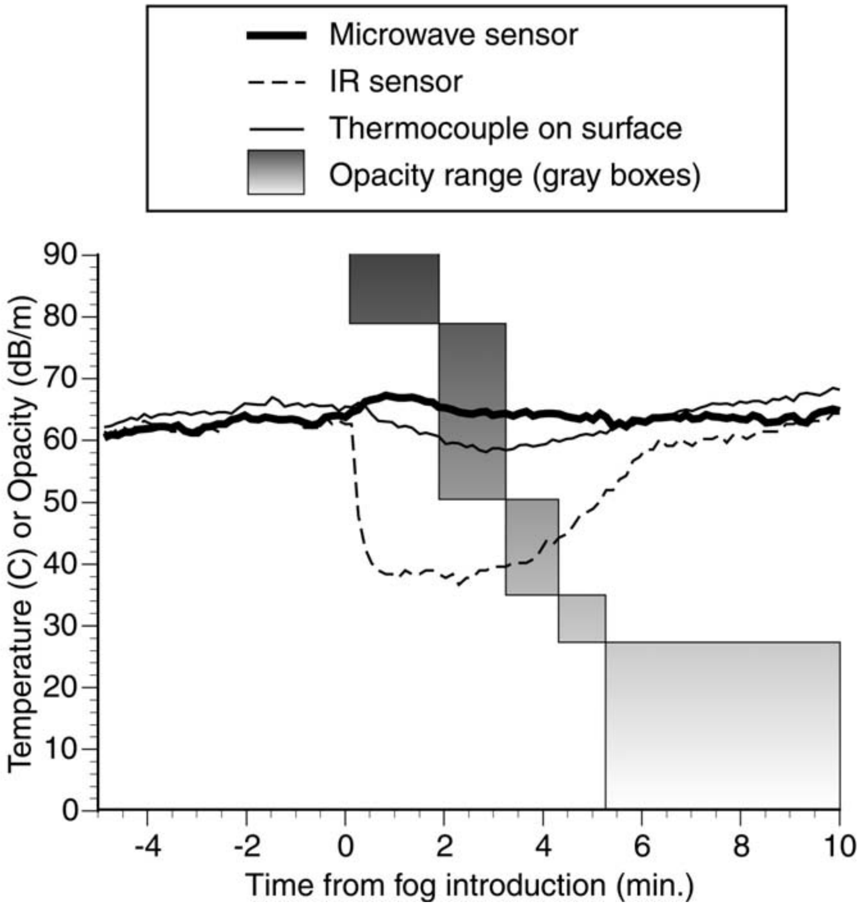

Fig. 5. Results of laboratory test using water fog. Note that IR sensor data show approx. -20 C error while fog is present, while microwave sensor data track thermocouple data within about ±5 C. (from Ref. [1])

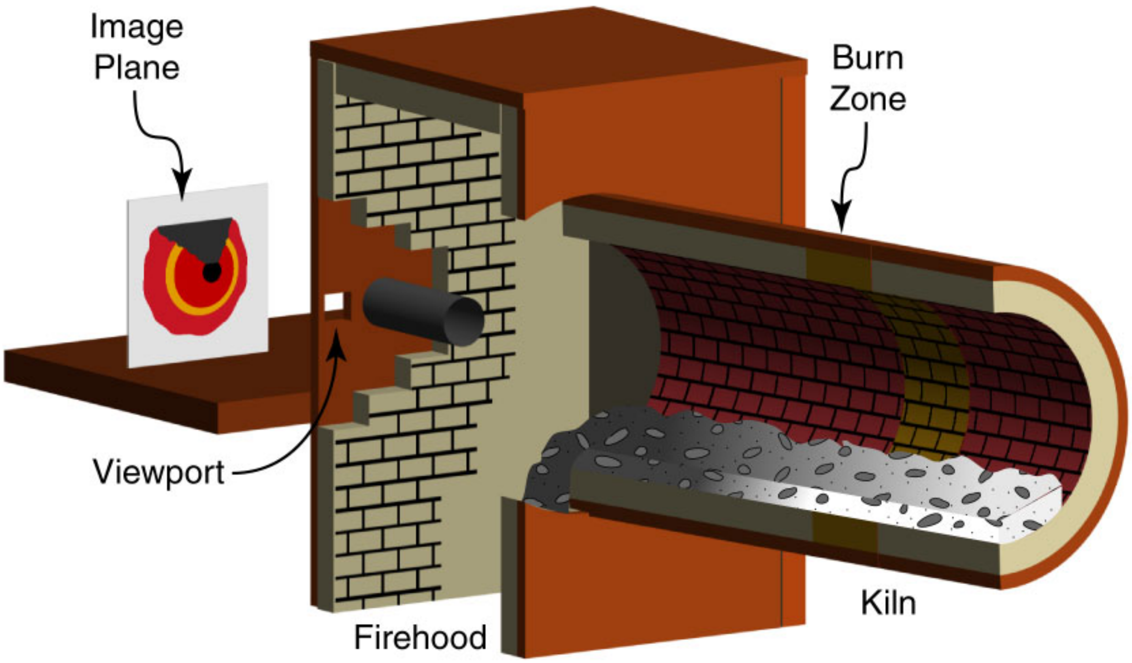

Fig. 6. Cross-section of kiln showing radiometer antenna positioned on image plane, viewport, cylindrical burner nozzle, and location of highest-temperature "burn zone" (not to scale).

Appendix A

Final Task Schedule

Final Task Schedule

Task Number	Task Description	Task Completion Date				Progress Notes
		Original Planned	Revised Planned	Actual	Percent Complete	
1	Complete Radiometer Assembly	06/01/03		6/15/03	100%	Completed
2	Radiometer Verification Tests	08/01/03	11/01/04	12/01/04	100%	Completed
3	Complete Field Trials	04/01/04	3/1/05	3/14/05	100%	Completed
6	Project Management	12/01/04	4/24/05	7/13/05	100%	Completed

Appendix B

Final Spending Schedule

Final Spending Schedule **Project Period:** 07/25/02 to 04/24/05

Task	Approved Budget	Final Project Expenditures
Milestone 1 Radiometer Assembly	130,000	130,000
Milestone 2 Radiometer Verif. Tests	51,962	51,962
Milestone 3 Complete Field Trials	89,041	89,041
Milestone 4 Project Management	27,724	19,662
Total	298,727	290,665
DOE Share	199,990	191,928
Cost Share	98,737	98,737

Appendix C

Final Cost Share Contributions

Final Cost Share Contributions

Funding Source	Approved Cost Share		Final Contributions	
	Cash	In-Kind	Cash	In-Kind
Texas State University	20,760	57,977	20,760	57,977
University of Texas		20,000		20,000
Total	20,760	77,977	20,760	77,977
Cumulative Cost Share Contributions				98,737

Appendix D

One Unit of Proposed Technology:

The unit of proposed technology is a cement kiln with an incoming feedstock feed rate of 317 tons/hour. The output of the kiln is hot clinker with a somewhat lower mass because of the removal of any remaining carbon dioxide from the calcium carbonate in the feedstock. The Texas-Lehigh unit on which this example is modeled is a "pre-calciner" kiln in which the feedstock is preheated in a separate unit ahead of the rotary kiln, with a separate fuel supply (not considered in this analysis). The kiln is heated by pulverized coal. The coal feed rate, feedstock feed rate, and other operating parameters which affect the quality of output and fuel economy of the system are under the manual control of an operator. The percentage of free lime (%FL) is the primary quality factor that is monitored by the operator. The %FL is a strong function of the peak kiln temperature. In the system using the proposed microwave temperature measurement technology, the operator can directly observe the peak kiln temperature in real time. This allows him to make adjustments of feed rates in response to changing conditions within three to five minutes. We assume that with the use of the proposed technology, the operator can limit kiln temperature variations to one-half of their former average value without the proposed technology, and can further reduce the average kiln temperature by 1% without compromising product quality. Based on experimental observations that the average kiln temperature variations without the proposed technology were on the order of ±4% (8% total), this means that average temperature variations with the proposed technology will be on the order of ±2% (4% total). We further assume for the purposes of calculation that the kiln temperature is directly proportional to the coal feed rate. Although this is a theoretical simplification, we do not have the extensive data available which would be required to create a mathematical model of the kiln system that includes the interactions among kiln temperature, kiln torque, kiln drive power consumption, feedstock feed rate, and other factors.

One Unit of Current Technology:

One unit of the current technology is identical to the unit of the proposed technology, with the exception of the absence of the proposed microwave temperature sensor. Currently, the kiln under study operates at a typical feedstock feed rate of 317 tons/hour and consumes an average of 9 tons/hour of coal as fuel. The average variations in kiln temperature observed during an eight-hour field test were ±4% (8% total). We assume for the purposes of this analysis that coal consumption is directly proportional to kiln temperature. In the current technology, the %FL quality figure can be measured directly only after a delay of about 45 minutes while the processed feedstock travels from the kiln output through a cooler, is sampled manually, and chemically analyzed. This inevitable delay in kiln control means that energy-wasting upset conditions often are not dealt with until 45 minutes after they begin. The use of a real-time temperature monitor for the kiln as in the proposed technology above will reduce or eliminate such delay problems.

Discussion of Energy Savings:

The assumptions used in calculating the following values for energy savings are as follows:

1. The kiln utilization rate (percentage of time the kiln is in operation) is 94%. This is consistent with an annual two-week shutdown for scheduled maintenance plus occasional unplanned shutdowns. This is an experimental value based on discussions with plant personnel.

2. Natural gas is used to fire the kiln 5% of the time. This is consistent with the practice of firing with natural gas when the coal pulverization system is unavailable due to needed repairs or maintenance. This is an approximate experimental value based on discussions with plant personnel.

3. Natural-gas firing requires twice the heat energy input of coal. This is because the natural-gas flame is less effective at transferring heat to the feedstock.

4. The coal used is minimum-grade bituminous coal, with a heat value of 10,500 Btu/lb. This is an approximate experimental value based on discussions with plant personnel.

Energy Savings Metrics

	A	B	C=A-B	D	E=CxD
Type of Energy Used	**Current Technology (Btu / yr / unit)**	**Proposed Technology (Btu / yr / unit)**	**Energy Savings (Btu / yr / unit)**	**Estimated Number of Units in U.S. by 2010 (units)**	**Energy Savings by 2010 (Btu / yr)**
Oil / Gasoline	0	0	0	120	0
Natural Gas	1.557×10^{9}	1.541×10^{9}	1.56×10^{7}	120	1.87×10^{9}
Coal	1.557×10^{10}	1.541×10^{10}	1.56×10^{8}	120	1.87×10^{10}
Electricity (@ 10,500 Btu / kWh)	2.62×10^{7}	2.62×10^{7}	0	120	0
Total Per Unit	1.713×10^{10}	1.696×10^{10}	1.713×10^{8}	120	2.05×10^{10}

5. As stated above, use of the proposed technology allows the operator to reduce temperature variations in the kiln from ±4% to ±2% on average. This is a theoretical projection based upon experimental measurements of both kiln temperature and percent free lime (%FL). If the plant personnel can use the

temperature data provided by the new technology to improve both the stability of the %FL figure and the kiln temperature by a factor of two (from ±4% to ±2%), and can further offset the average temperature downward 1% so as to avoid "overburning", this will also result in an average energy saving of 1%. While this figure itself is theoretical, it agrees with estimates provided by plant personnel in discussions of the proposed technology. The resulting product will also have a more consistent quality as measured by %FL.

The figure of 1% energy savings agrees with the energy savings projected in the original proposal, which was also 1%.

Addendum added Jan. 2006: Ath the time the information in Appendix D above was compiled, we had not completed evaluation and analysis of data taken on a March 2005 field experiment. During this experiment, about eight hours of continuous temperature data were taken with the instrument, as well as hourly measurements of %FL (percent free lime), an important measure of cement quality. According to several authorities, the %FL is a good indicator of the time-temperature history of the product. Good-quality cement should have between 1% and 3% free lime. A kiln temperature that is too high wastes energy and results in less than 1% free lime, while too low a temperature can result in 3% free lime or greater, other things being equal.

A paper entitled "Correlation of Product Chemistry with Cement Kiln Temperature Measurements Using Microwave Radiometry" describes the results of this field trial. While an absolute temperature calibration could not be performed because of process factors, the radiometer produced estimated temperature data which ranged over the eight-hour period from a low of about 1350 C to a high of about 1470 C, with an estimated error of ±25 C. The hourly chemical analyses of free lime showed that the period of highest temperature corresponded to the lowest measurement of free lime (1% ± 0.1%), and the time of lowest temperature corresponded to the highest %FL (2.2% ±0.1%). This experimental data shows the usefulness of the temperature measurement instrument we have developed in monitoring real-time data that can be used to produce a more tightly-controlled time-temperature history for the product. We believe this experimental data substantiates the claims made in Appendix D above concerning the operator's improved ability to control the kiln temperature with the aid of the instrument developed. While it remains to implement such a control system using the instrument, the scope of this part of the project was limited to demonstrating the instrument's performance in actual industrial conditions, which has been done.

The above-referenced paper will be submitted to the *Journal of Microwave Power and Electromagnetic Energy*, and when it is published, a copy will be provided upon request.